STUDIES IN

THE J-TRANSFORMATION OF SCATTERED X-RADIATION.

BY

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Synopsis.

In the investigations on Scattered X-radiations described in the following pages, the J_1, J_2 and J_3 series of absorption-edges and lines in various substances have been demonstrated. What is now called the J_3-series was discovered by Barkla and White[1] in 1916, using a primary X-radiation. A similar absorption discontinuity was also discovered by Barkla[2] by using the characteristic radiations of the K-series. There was however, a discrepancy between the values of the critical mass-absorption-coefficients obtained for the characteristic radiations and those obtained from experiments on heterogeneous primary rays. It originally appeared probable that this discrepancy was due to the difference in the constitution of the two beams - one a heterogeneous bundle of radiation giving presumably a continuous spectrum within narrow limits and the other, a characteristic radiation giving practically a line spectrum. The results embodied in this paper, however, show that these two form quite

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(1) Barkla and White, Phil. Mag. Oct.1917.
(2) Barkla. Phil. Trans. 1917.

distinct series, J_2 and J_3. In fact there is evidence that lines of the three distinct series J_1, J_2 and J_3 can be obtained in one series of observations with scattered X-radiations. These involve what we have called the J-transformation of an X-radiation.

The characteristics of this transformation which have been investigated, using a Scattered X-radiation are briefly the following:

(1) There are definite critical values for mass-absorption coefficients at which these J-absorption edges and lines appear. The critical value is different for different absorbing substances. It is characteristic of the absorbing material.

(2) The magnitude of the J-absorption is also different for different substances.

(3) The phenomenon is conditional on factor or factors other than wavelength and the material of the absorbing substance.

(4) On the assumption that a change of wavelength is always associated with a change of absorption in <u>all</u> substances, the J-phenomenon does not involve any change of wavelength during transmission.

(5) The phenomenon is definitely associated with an average absorption-coefficient of a radiation and not with a certain wavelength so that there can be a change of X-ray activity without a corresponding change in wavelength.

The application of these generalisations to the scattered X-radiation has led to some very important conclusions as regards scattered X-radiations which have recently received a great deal of attention on account of the startling theory of wavelength-change on scattering, proposed by A. H. Compton[1] and Debye.[2] The main conclusions are:-

I. The difference that is generally observed between the penetrating powers of the primary and secondary (scattered) radiations is due to the fact that the scattered radiation exhibits the J-phenomenon while the primary does not, in passing through the absorbing substance used to test the absorbability of these radiations. The difference appears abruptly at the critical penetrating powers for the J-discontinui-:ties. Apart from these differences definitely associated with the testing material, the scattered and the primary radiations are exactly alike.

II. Between two discontinuities the difference between the mass-absorption-coefficients for the primary and secondary radiations is constant. It only depends on the material of the absorbing substance. According to Compton - Debye theory on the contrary, the change in wavelength should be constant.

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(1) A.H. Compton, Phys.Rev. May 1923. & Dec.1923. Bull. N.R.C. Oct.1922. Phys.Rev. Aug.1924.
(2) P.Debye, Physik. Zeitschr. 24, 161, 1923.

III. Since the J-transformation is conditional on factor or factors other than the nature of the substance traversed and wavelength of radiation, we get <u>either</u> an equality of the penetrating powers of the primary and secondary radiations <u>or</u> a marked difference between the two. The "modified and the "unmodified" scattering are not therefore, simultaneous but only alternative.

IV. The difference between the penetrating powers of the secondary and primary radiations is independent of the angle of scattering. This again is contradictory to the theory of change in wavelength, proposed by Compton and Debye.

Thus the results of our investigations seem totally incompatible with the Compton-Debye theory. The only possibilities of reconciling the two are discussed in detail in the following pages.

Before presenting the actual results of the investigations on the absorption of Scattered X-rays, we propose to give below, by way of an introduction, a general survey of what has been done along this line by previous experimenters and indicate the way in which we have been able to come to definite conclusions regarding scattered X-radiations.

Introduction.

It has long been known that certain conditions were necessary in order to obtain evidence of the purest scattering of X-radiation. As early as 1903, Barkla pointed out that very soft X-radiation must be employed in order to obtain scattering which could be explained in its polarisation, distribution and intensity, precisely by the application of the classical theory as given by Sir J.J.Thomson. It was this scattered radiation - obtained under certain conditions from elements of low atomic number - which was found[1] exactly like the primary radiation in its penetrating power, over a wide range of wave-lengths; while what appeared to be a similar scattered radiation under other conditions, was observed to be distinctly more absorbable than the primary X-radiation exciting it.

The conditions showing the difference between the primary and scattered radiation in their penetrating powers appeared to be more general inasmuch as they have been obtained by many experimenters[2] on the subject, from the very earliest times.

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(1) Barkla & Sale, Phil.Mag. April 1923.

(2) Barkla, Phil.Mag.1904.
Sagnac, Comptes Rendus 1904.
Beatty, Phil.Mag.
Sadler & Mesham, Phil.Mag.24,1912.
J.Laub, Ann.de Phys. 46,1915.
J.A.Gray,Frank.Inst.Jour.Nov.1920.
A.H.Compton, Phys.Rev.18,1921,Nature 107,1921,Phil.Mag.Nov. 1923.
J.A Crowther, Phil.Mag. 42,1921.
R.T.Dunbar, Phil.Mag.Jan.1925.

It was only in the experiments of S.J.Plimpton[1], besides those of Barkla, that there was evidence of a very close equality in the penetrating powers of homogeneous primary and secondary X-radiations scattered from light elements. It is interesting to notice however that a repetition of these experiments by A.H.Compton[2] under appar-:ently identical conditions, showed that the secondary was decidedly more absorbable than the primary X-radiation.

There are two obvious reasons for any difference appearing between the secondary and primary radiations. The first is the preponderance of constituents of longer wave-length in the scattered beam, when a heterogeneous radiation is employed; and the second is the superposition of a tertiary radiation excited in the scattering substance by the swift electrons constituting the secondary corpuscular radia-:tion. The effect due to either of these scources, is vanishing-:ly small in the case of scattering from thin sheets of light elements. The appearance, under certain cindi tions, of a secondary radiation, scattered from light elements and differ-:ing from the primary, therefore indicated a transformation, <u>either</u> in the emission of a new series of characteristic radiations by the scattering substance, <u>or</u> in a change of wave length of the radiation in the scattering process.

The first alternative, namely the hypothesis of a new characteristic radiation emitted by the radiator.at one time

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(1) S.J.Plimpton, Phil.Mag., 42 Sept,1921.
(2) A.H.Compton, Nature, Nov. 17, 1921.

looked very promising from various considerations. The large discrepancies between the values for the coefficient of scattering, obtained by different observers, were considerably greater than any possible experimental error could explain, and suggested that the radiation was not all scattered radiation but that it was accompanied by considerable amounts of X-radiations of different origin. Crowther's[1] value of $\frac{\sigma}{\rho}$ for Aluminium was as high as 1.18 and his later experiments[2] by a different method gave values of $\frac{\sigma}{\rho}$ for Aluminium and paper as .28 and .27 respectively. These results - as well as the fact that the distribution of intensities of scattered X-radiation round the radiator[3] varies considerably with the quality of the primary radiation employed to excite it and in some cases with the thickness[4] of the radiator - seemed to fit in very well, qualitatively at any rate, with the hypothesis of an additional fluorescent X-radiation. The strongest support however, came from the J-discontinuities of Barkla, first recorded in the Phil.Trans.1917 and later in another paper by Barkla & White.[5] As the frequency of an X-radiation was gradually increased, either by increasing the speed of the electrons exciting it or by selection of characteristic radiations from elements of increasing atomic number, there appeared a sudden increase

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(1) Crowther, Proc.Roy.Soc. A. LXXXVI 1911.
(2) Crowther, Proc.Roy.Soc. A. LXXXVI 1912.
(3) Crowther, " " " " " "
(5) Barkla & White, Phil.Mag. Oct.1917.
(4) Crowther, Proc. Camb.Phil.Soc. XVI, 1911.

in the absorption of the radiation by any particular substance. The discontinuity was observed at a particular frequency (as measured by the absorbability) characteristic of the element and increasing with the atomic number of the element. The rise in absorption in a substance was also accompanied by a sudden increase in ionisation when the substance was in the gaseous condition and by an increase in the electronic emission when in the solid state. Such a close similarity with what is generally observed in association withthe emission of a characteristic radiation of series K,L,M, strongly suggest:ed the existence of a characteristic radiation of higher frequency than the K-radiation - called the J-characteristic radiation since the discontinuity in a certain substance appeared at a "frequency" much higher than that associated with the K-radiation for the same substance. Overwhelming as the evidence for such a radiation might have appeared, direct experiments of Barkla and Sale, however, failed to furnish evidence of the J-characteristic radiation. Barkla[1]'s later experimental results on the other hand, revealed many striking features of the J-discontinuities which marked out the phenomenon as quite distinct from the production of X-ray fluorescence.

The following are two important results of Barkla & Sale which we have also subsequently fully verified:

(1) The ratio of the intensities of the secondary and primary radiations (as measured by the ionisations produced by them) showed no discontinuity over a wide rage of wave-lengths.

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(1) Barkla, Phil,Mag, May,1925.

(2) As the wave-length of a primary X-radiation was gradually diminished, the radiation scattered from light elements was found, under certain conditions to be exactly like the primary radiation (as measured by the absorbability) over a long range of wave-lengths; but a change suddenly occurred at a particular hardness of the primary radiation.

The latter result (2) indicated either the admixture of an unidentified fluorescent radiation or just possibly a transformation on scattering, suddenly taking place at a particular frequency: but the former result (1) clearly proved that the difference appearing in the secondary radia-:tion could not be attributed to either of these; for in both cases, a discontinuity would have been noticed in the ionisa-:tion produced by scattered radiation, at the point where a sudden increase in the absorbability of the secondary beam was observed.

With regard to the hypothesis of a change of wave-length, in the process of scattering, some very bold advances have recently been made from a classical as well as from a quantum point of view. In a number of papers A.H.Compton[1] has given a very startling theory of scattering based on a quantum principle, which requires a change of wave-length on scattering (at any rate when the scattering electron receives an impulse sufficient to eject it from the atom).

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(1) A.H.Compton, Phys. Rev. May 1923 & Dec.1923. Bull N.R.C. Oct.1922. Phys.Rev.Aug.1924.

P.Debye[1] also arrived at the same formula for the change of wave-length on scattering, from similar considerations.

The hypothesis of a change of wave-length on scatter-:ing appeared impossible according to the classical conception of X-radiation with long wave trains; although originally, when X-rays were considered as radiations consisting of discontinuous pulses, there appeared the possibility of a change in the properties of radiation produced by the process of scattering by electrons or groups of electrons subject to restraining forces within the atom. Recently the possibility of such a wave-length change on scattering has been worked out by K.Försterling[2] and O.Halpern[3] along a semi-classical line. They have taken into account the pressure of radiation which was not considered in J.J.Thomson's treatment of scattering. With the help of one quantum assumption, they have been able to show that even on the classical wave theory there can be a change of wave-length on scattering and that the change is given exactly by the same formula as that of Compton & Debye. Other attempts[4] have also been made to arrive at this formula for the wave-length change from the classical point of view.

Spectroscopic investigations of Scattered X-radiation

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(1) P.Debye. Physik, Zeitschr. 24,161,1923.
(2) K.Försterling, Physik, Zeitschr. 25,313,1924.
(3) O.Halpern, Zeits. f. physik 30,153,1924,
(4) C.Eckart & F.W.Bubb, Phys,Rev. Dec.1924.

by A.H.Compton[1], P,Ross[2], Bergen Davis[3], Compton & Woo[4], Becker[5], Becker,Watson, Smythe, Brode & Mottsmith[6], F.Dessauer & R.Herz[7], M.de Broglie & A.Dauvillier[8], A Dauvillier[9], Allison & Duane[10], Kallmann & Mark[11], G,Hagen[12], H,M,Sharp[13] and others appear more than amply to have justified the theory of wave-length change on scattering. Their experiments have without any doubt revealed two distinct lines in the spectrum of scattered X-radiation showing that in addition to an "unmodified" radiation of the same wave-length as the primary, there also exists a "modified" radiation of longer wave-length - the change in wave-length agreeing perfectly with theory.[14]

Convincing as these results might appear when judged by themselves, recent absorption experiments performed with scattered X-radiations in this laboratory have yielded results

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(1) A.H.Compton, Bull.N.R.C. XX.Oct.1922.Phys.Rev.June & Nov.1923. Aug.1924.
(2) P.Ross,P.N.A.S.9.246.1923,P.N.A.S.Sep.1925,Phys.Rev.22,1923
(3) Bergen Davis - Paper before section B of A.A.A.S.at Cincinnati Dec.1923.
(4) Compton & Woo P.N.A.S.10,271,1924, Woo,Phys.Rev. Feb.1926.
(5) Becker, P.N.A.S. 10.342, 1924.
(6) Becker,Watson,Smythe, Brode & Mottsmith,Phys.Rev.23,763,1924.
(7) F.Dessauer & R.Herz. Zeits. f. Physik 27 1st half 1924.Aug.28.
(8) M.de Broglie & A.Dauvillier, Comptes Rendus 179 July 7,1924.
(9) A.Dauvillier loc.cit.178 June,16.1924
(10) Allison & Duane. Phys.Rev. Sept. 1925.
(11) Kallmann & Mark. Die Naturwissenschaften 13(Heft 14)277,1925.
(12) G.Hagen, Ann. der Physik No.20.Vol.4, Band 78.Dec.1925.
(13) H. M. Sharp, Phys.Rev. Dec.1925.
(14) Absorption measurements by A.H.Compton,(Phil.Mag.Nov.1923) curiously agree with his theory in spite of the presence of an "unmodified" radiation as shown in the spectrum of scatter-:ed X-rays. R.T.Dunbar's results of absorption experiments (Phil.Mag.Jan.1925) also fairly agree with the Compton-Debye formula, although there are some very abnormally high values for the mass absorption coefficient of the scattered radiation.

which cannot be reconciled in any way with the hypothesis of a wave-length change: they have on the other hand, given strong evidence to the contrary. It has however been possible in these absorption experiments[1] to show that there is a transformation in the scattered X-radiation and that this transformed radiation is neither a fluorescent radiation nor a scattered radiation of longer wave-length. The transformation has been observed entirely outside the scattering substance and has been proved beyond doubt to be the same phenomenon as was observed by Barkla & White to occur in the absorbing material used to test the absorbability of the scattered radiation. The association of this transformation - the J-transformation - with the scattered radiation is quite accidental - in the sense that it is not fundamental; for exactly the same phenomenon may be shown, in fact it has been shown, with a primary X-radiation.

The existence of this J-transformation in scattered X-radiation, subsequent to the fundamental process of scattering, makes one extremely critical as regards the interpretation of the second spectral line observed by Compton and others in their spectroscopic investigations with scattered X-radiation; for the measurement of wave-length is dependent, not only on the adequacy of the theory of diffraction[2], but also on the assumption of the

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(1) See Barkla & Khastgir, Phil.Mag.Jan.1925 & Nov.1925.
(2) Clark & Duane obtained certain abnormal maxima which did not obey Bragg's law (P.N.A.S.IX 4,131,1923 & VIII 5,90 1923) Theoretical possibilities of abnormal reflection from a crystal have been given by McKeehan (Opt.Soc.Am.& Rev,Soc.Inst. Dec.1922,p.989) and Smith (Phil.Mag.Jan.1925).

absence of any unforseen phenomenon. A detailed knowledge of the J-transformation is therefore essential before any interpretation of the spectroscopic results could be made in terms of this phenomenon.[1] If on the other hand, the exact precision with which the spectroscopic results agree with the Compton-Debye formula for various angles of scattering, is taken to indicate a change in the wave-length of the scattered radiation - there must needs be a complete separation of the activity of a radiation (as measured by absorption, ionisation, corpuscular emission etc) from what is called the frequency; for investigations on absorption of Scattered X-radiation have shown that experimental results are not by any means compatible with the theory of a change of wave-length.

In the following pages are given the results of these absorption experiments which will bring out very clearly their disagreement with Compton's formula, and which, in addition, will show that the phenomena appearing in the investigation of scattered X-radiation by ionisation-absorption method are mere instances of the much more general J-phenomenon of Barkla.[2] They will also reveal features which will enable one to under-:stand the nature and meaning of the J-transformation of scattered X-radiation.

Apparatus & Method.

Very great accuracy has been secured in the detection

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(1) Khastgir & Watson, Nature, April 25, 1925. Wave-lengths of K_α K_β & K_γ when plotted against atomic number showed irregularities at points where the J-discontinuities were expected to occur for calcium of the Calcite crystal in the spectrometer.

(2) Barkla, Phil.Mag, May.1925.

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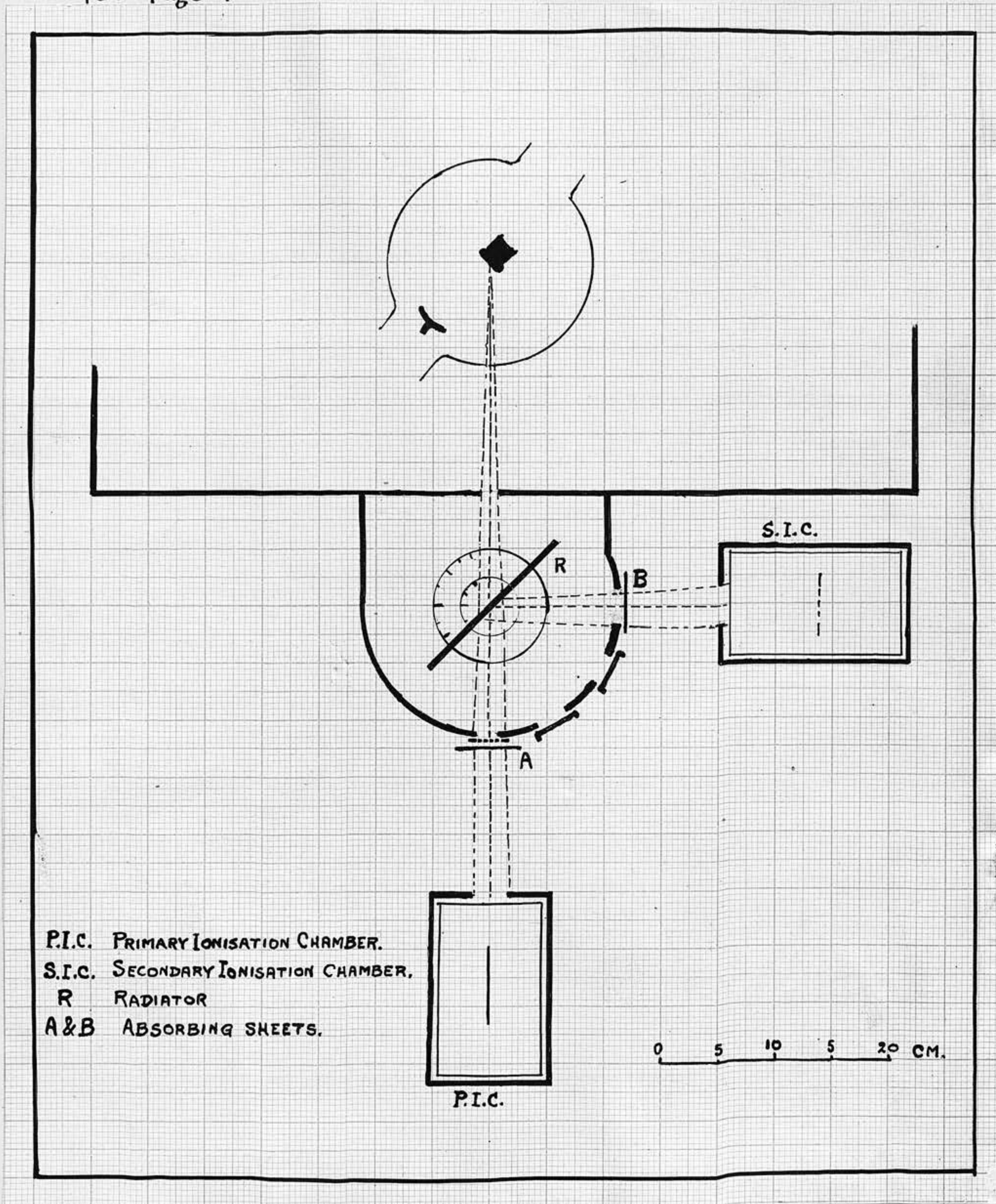

FIG. 1.

and measurement of any difference occurring in the scattered radiation. This was obtained not by measuring the absorption coefficients of both primary and secondary beams and then comparing these, but by a very simple method, the description of which is given below:

Two similar ionisation chambers filled with SO_2, and connected to systems of ordinary gold-leaf electroscopes, were employed to measure the ionisation produced, one by the secondary radiation from paper, and the other by the primary beam or rather by fine pencils of the primary radiation from various portions of the beam. The ratio of ionisations was obtained for various wave-lengths. The ratio $\frac{\text{Secondary ionisation}}{\text{primary ionisation}}$ or S/P was found constant, the variation in some experiments amounting only to about 1 per cent. Similar sheets of aluminium or any other absorbing substance were placed at A and B (fig 1) in the paths of these two beams on their way to the ionisation chamber and the ratio of the ionisations was again determined for corresponding wave-lengths. Let us call it S'/P'. If the ratio remains unchanged, it indicates that the absorption of the secondary and primary radiations is equal, and if there is a fall in the ratio, it follows that the secondary is more absorbable. This test was found to be very sensitive for a difference between S/P and S'/P' of well within 2 per cent could be detected beyond any doubt, especially when the thickness of the absorbing substance intercepting the two beams was so arranged as to diminish the ionisation by about 50 per cent.

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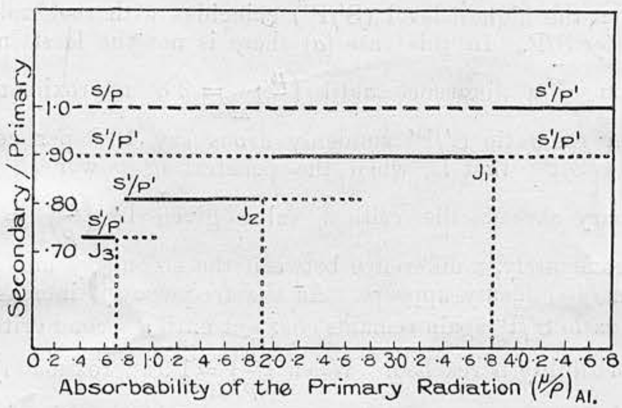
Fig. 2.



Broken line - - - - - - - is "unintercepted ratio" S/P.
Continuous line ——— is "intercepted ratio" S′/P′.
Dotted line .... is occasional "intercepted ratio" S′/P′.

FIG. 2.

In any one experiment however, the thickness of the absorbing sheets was kept constant throughout the whole range of wavelengths employed. In using this method of detecting and measuring the changes, if any, in the absorption coefficients of the primary and secondary radiation, it appears that much higher accuracy can be obtained than by employing the spectroscopic method, and with less complication.

Experimental Results.

The results of a very large number of experiments of this kind with aluminium are given in fig. 2, where the ratios of the ionisations produced by the secondary and primary beams with and without the two similar sheets of an intercepting substance (viz. S/P and S'/P') are plotted for various radiations against their mass-absorption coefficients. The absorption coefficients were measured in the usual way from a 50 per cent absorption.

The ratio (S/P) of the ionisations produced by the <u>unintercepted</u> secondary and primary beams, as has been already mentioned, was found remarkably constant throughout a long range of wavelengths. This might of course be expected if there is a balance of two opposing variations, an increase in the frequency of the primary being accompanied by diminished intensity of secondary radiation, combined with increased absorbability and ionising power compared with the primary. Compton's formula also gives to a first approximation an unchanged ratio when the radiation employed is not sufficiently short. *A priori* such a balance is improbable. and the constancy of the ratio is so marked that it appears to indicate a definite absence of variation of either, rather than an approximate balance between the two. The results of experiments in which both primary and secondary beams were intercepted by similar absorbing sheets have, however settled this point without any ambiguity.

The ratio S'/P' i.e. the ratio of the ionisations produced by the secondary and primary radiations after transmission through two equal thicknesses of an absorbing substance was found <u>either</u> exactly equal to <u>or</u> very markedly lower than S/P, the correspompding ratio when the beams were unintercepted. This showed that the primary and secondary radiations were <u>either</u> alike in their penetrating powers <u>or</u> the secondary was distinctly softer. Normally, the difference appears at a particular absorbability of the beam, when the value of S'/P' no longer remains equal to S/P, but becomes distinctly less. This lower value of S'/P' remains remarkably constant until other sudden increases of absorption take place in the secondary radiation. Evidence has been obtained of three such distinct discontinuities - which have been called the J_1, J_2, & J_3 discontinuities reckoned from low to high frequencies i.e. moving from right to left of Fig,2. The values of the ratio S'/P' therefore fall on four horizontal lines, the three steps corresponding to the three levels of activity of scattered X-radiation in the absorbing substance. Using a particular thickness of an absorbing substance the magnitude of the drop after the J_1 discontinuity has a definite value:- the precise amount depending on the thickness of the absorbing material used to intercept both beams. This normal state of affairs has been described under Case A. Another case (Case B) must however be described, for all the results obtained in hundreds of experiments with apparatus of different forms and using different X-ray tubes, different ionisation chambers, different types of interrupters etc., are included in these two cases. In case B a constant difference of absorption coefficients for primary and secondary radiation is observed from the very beginning - with or without further increases of absorption at higher frequencies. It should be emphasised here that the two cases are definitely **alternative** ; the condition or conditions controlling the phenomenon are as yet unknown.

Experimental details.

Before proceeding to a fuller account of the two cases some attention should be given to the description of the experi- :mental conditions so that these can be compared with those of other experiments which give different results. Precautions taken to ensure a true comparison of the primary and secondary radiations are also given.

The source of X-rays in all the experiments was a gas-filled tube, usually of "Reliance" type with platinum anticathode, Tungsten and Palladium anticathodes were also tried with exactly similar results. The source of high tension current was an ordinary 12" induction coil, operated by a "Sanax" mercury break, the primary current being obtained from accumulators of a total voltage of 20. The hardness of the X-ray tube was adjusted usually by varying the current through it, by regulating the gas pressure within the tube with the help of the "softener" and by manuplating the speed of the interrupter. The radiation employed was very heterogeneous, as, in general, no absorbing sheet was used to filter the beam. (Mention is made whenever hardness was varied by filtering the heterogeneous radiation.).

The scattering substance employed was usually 25 sheets of filter paper. weighing .194 gm. per sq.cm.; mention is made when other thicknesses were used. The sheets of filter paper were held in an aluminium frame which could be adjusted to any angle. The scattered radiations emerging from the second face of the sheets were studied at three different angles 90°, 60° and 30° to the primary radiation - the radiator in each case being placed exactly symmetrically with respect to the primary and scattered radiations emerging from the scattering substance. Since the sheets were equally inclined to the primary and secondary radiation, errors due to absorption in the paper affected both beams in the same degree; so in comparing the ionisation produced by the scattered radiation, with that by the primary, there was practically no error due to differential absorption.

The ionisation chambers employed in later experiments were each of length 15 cms. and diam. 9½ cms., with very light aluminium electrodes in the centre which were properly insulated and surrounded by guard rings charged from a dry battery of 264 volts. The outer surfaces of the chambers were earthed and the aluminium electrodes had connections with the gold-leaf systems of two similar ordinary electroscopes. The electros-:copes were charged from the city supply at 230 volts.

Some of the precautions taken to ensure a proper comparison between the primary and secondary radiation, are enumerated below:

(1) It seemed not improbable that the narrow pencil of primary radiation, such as is received in the primary ionisation chamber, was not a true measure of an incident primary beam of considerable cross-section. To avoid this uncertainty the beam incident on the radiator was made as narrow as possible and instead of one pinhole a number of very small pinholes evenly distributed over an area of the lead screen, were used to ensure that a fairly representative bundle of rays from the primary was obtained.

(2) Smaller apertures were also necessary to guard against the effects of superposition of soft fluorescent radia-:tion from the anticathode as well as from the glass of the X-ray tube, for these oblique rays would produce a much greater effect, in proportion, in the secondary than in the primary, electroscope, the small apertures leading to the latter, being comparatively long and narrow.

(3) For similar reasons i.e. to avoid superposed fluores-:cent as well as scattered radiation, filtering sheets, particular-:ly of copper, were rarely used in hardening the incident beam

of X-rays. On a few occasions, when filters were used to harden the beam in the region of higher frequencies, they were always kept fixed throughout the experiment.

(4) The angle subtended at the window of the secondary ionisation chamber by the aperture in the path of the secondary beam and very near to the radiator, varied from 20^{o} to 15^{o}. Hence in these experiments the thickness of the absorber traversed by <u>the most oblique rays possible</u> is greater than the normal thickness only by 0.5 to 1 per cent. On an average, the error due to the obliquity of the rays could not exceed 0.5 per cent.

(5) The absorbing sheets were placed as far away from the ionisation chambers as possible. The distance of the secondary ionisation chamber in most of the later experiments was 20 cms. away from the radiator. The absorbers were placed at a distance of about 11 to 14 cms. from the same. The distance of the primary ionisation chamber was 28 cms. from the radiator. This precaution was necessary to avoid the scattered and fluorescent radiation, if any, coming from the absorbers and affecting the ionisation in the chambers. (The small difference of paths of the primary and secondary beams through air, produces quite negligible effect on the constitution of three beams; in fact the effect of absorption by air on either is relatively extremely small). For absorbing substances of high atomic number tests were made with regard to scattered and fluorescent radiations coming from them, by varying their

positions.

(6) Stray effects due to any possible extraneous radiation were looked for, especially in the region of the J-discontinuities. They were negligible and showed no effect of the kind observed and thus cannot be held responsible for these discontinuities.

Absorption measurements with X-radiations scattered at 90°.

Results obtained with aluminium when the angle of scattering is 90° are summarised below. Those for other substances such as, filter paper, copper, silver, tin and gold will be considered later. Absorption measurements with radia-:tions scattered at 60° and 30° will also be given subsequently.

Case A.

Beginning with very soft radiation when $(\mu/\rho)_{Al} = 7$ say, i.e. when the wavelength is about .75 Å.U. and gradually increasing the hardness of the beam, it has been found that the ratio $S'/P' = S/P$ very exactly i.e. the absorbabilities of the primary and secondary radiations are precisely alike. There is not the least indication of a difference until $(\mu/\rho)_{Al} = 3.8$ approximately, when the thickness of the aluminium sheets intercepting the primary and secondary radiations is about .05 cm. which cuts off about 50 per cent of the radiation. At this point the ratio S'/P' suddenly drops down 9 per cent below S/P; or in other words, when the penetrating power of the primary exceeds a critical value given by, $(\mu/\rho)_{AL} = 3.8$ approximately

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Fig. 3.

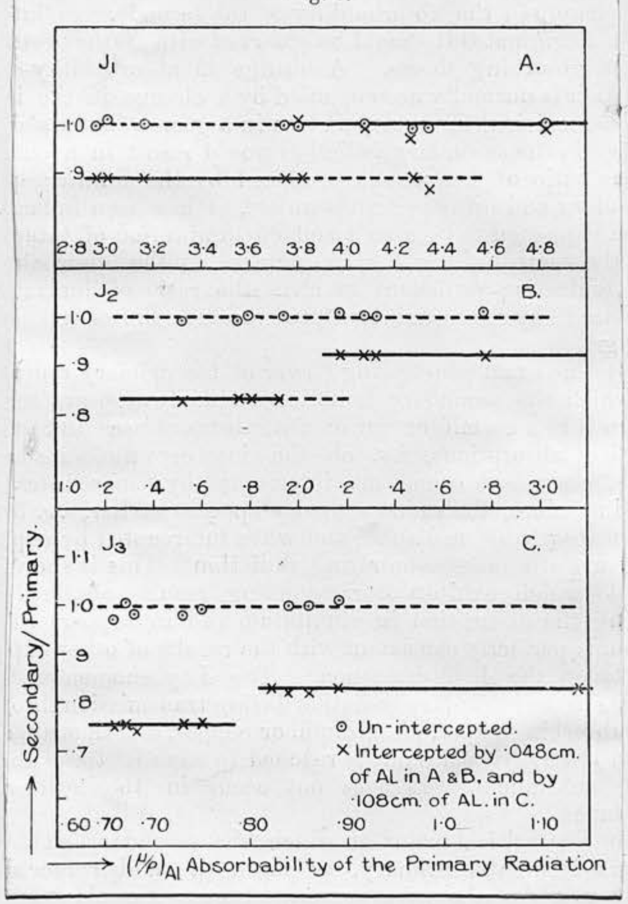

FIG. 3.

SEE TABLE I.

there is a sudden appearance of a difference between the primary and secondary radiations. This we have called the J_1-discontinuity. After the J_1-discontinuity, as the beam is hardened, the ratio S'/P' remains constant until at a second critical absorbability there is observed a further drop - the J_2-discontinuity. This appears when $(\mu/\rho)_{Al} = 1.9$ approximately. After this, as the beam is still more hardened, the ratio S'/P' again remains constant until a third critical point is reached: $(\mu/\rho)_{Al} = 0.7$ when there is a further drop of ratio S'/P' - the J_3-discontinuity. Indication of a fourth discontinuity was also obtained; the experiments were not sufficiently careful or numerous to justify any very definite statement regarding it. (See fig.3 and table I.)*

It should be pointed out that each discontinuity was passed over in both directions i.e. the step was passed over in the direction of increasing as well as of decreasing wavelengths. The steps always appeared at about the same spot, not only in one, but in a number of experiments.

Deductions from the experimental results:

It is quite clear that these sudden changes in the ration S'/P'(in the experiments described above) have their origin not in the radiator at all, either in the emission of a fluorescent radiation, or in a change of wavelength in the process of scattering; for in either case, the transformation ought to have been observed without the presence of these absorbing sheets. A change in the

* For tables see Appendix.

absorbability of a radiation is normally accompanied by a change in the ionising power of the radiation in a gas, so that a sudden change in the secondary radiation would result in a change in the ratio of ionisations (S/P) produced by the "unintercepted" secondary and primary beams , unless as has been already indicated there happens to be an exact compensation for increased absorbability by diminished intensity of the secondary radiation - a proviso which, considering the accuracy of the experimental results, is expecting altogether too much from a coincidence!

The only conclusion to which we can come from the results mentioned above is that the transformation observed in the form of various discontinuities - whatever may be its exact nature - has its origin in the intercepting substance; its explanation, therefore, must be sought in some anomalous absorption phenomenon taking place in the intercepting absorbing sheets. That this is nothing but the J-phenomenon of Barkla is evidenced by the fact that the J_2 & J_3 discontinuities for aluminium, appear in these experiments almost exactly at the same critical absorbabilities as in the experiments of Barkla on the J-phenomenon. Not only that, but all the results are precisely those to be expected from the application to the scattered radiation of the laws governing the J-phenomenon. Although the reason is not yet known why the scattered radiation should be more susceptible to the J-phenomenon than the primary radiation, direct experiments with scattered radiation alone have shown that in these experiments, at any rate, it is the

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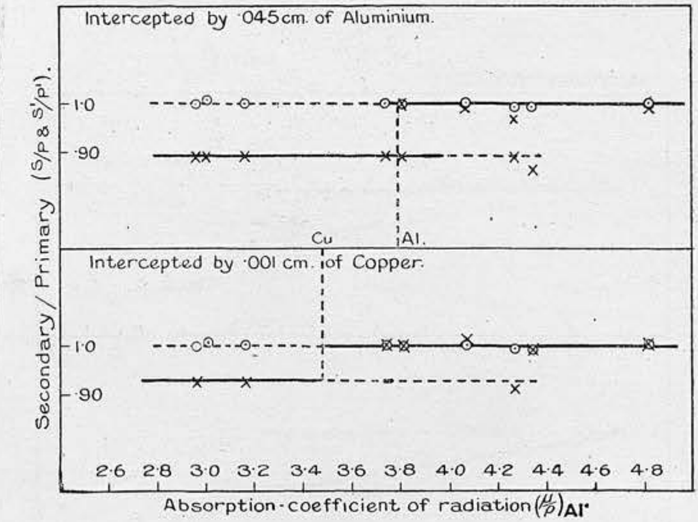
Fig. 4.



Circles denote "unintercepted ratio" S/P.
Crosses denote "intercepted ratio" S′/P′.

FIG. 4

SEE TABLE II.

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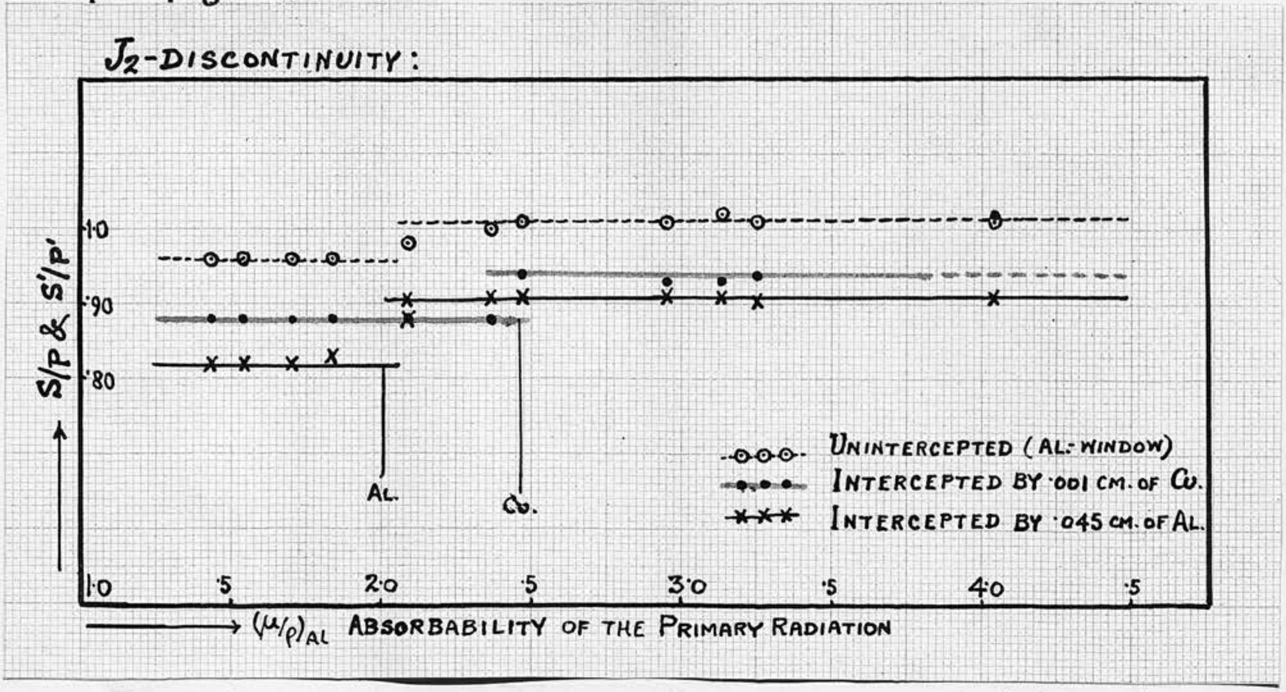
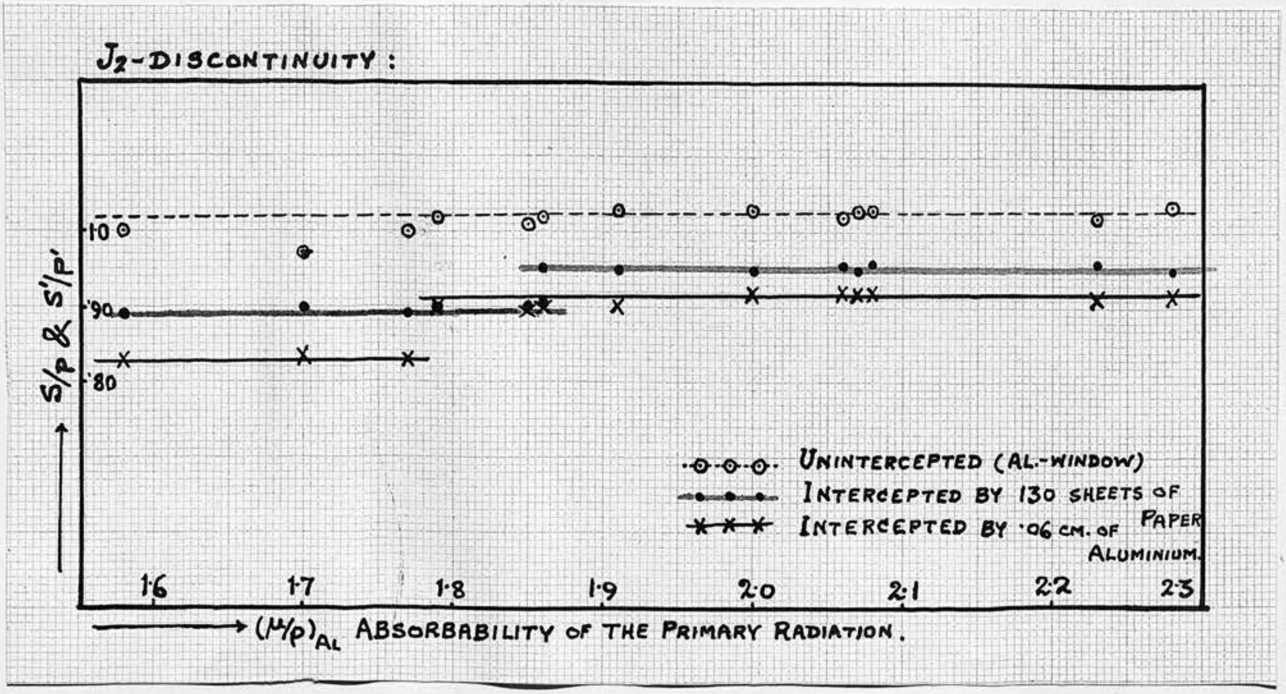


SEE TABLE II.

FIG. 5.



SEE TABLE III.

FIG. 6.

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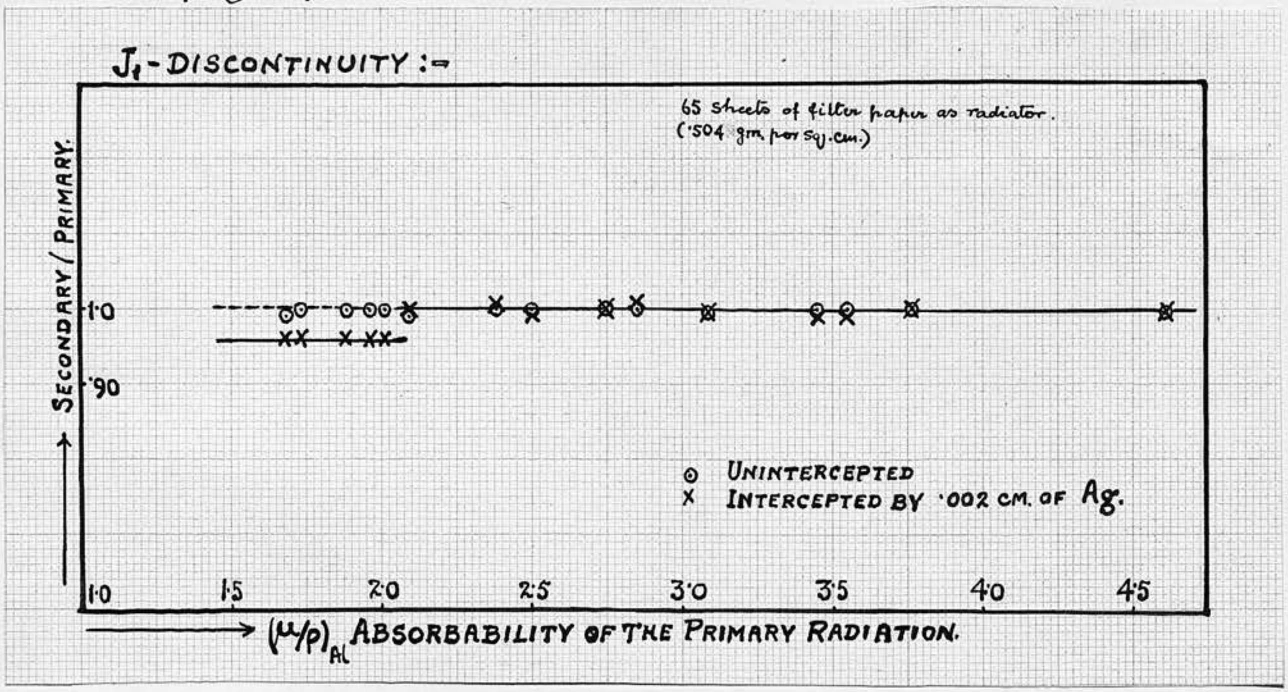

Fig. 7.

See Table IV.

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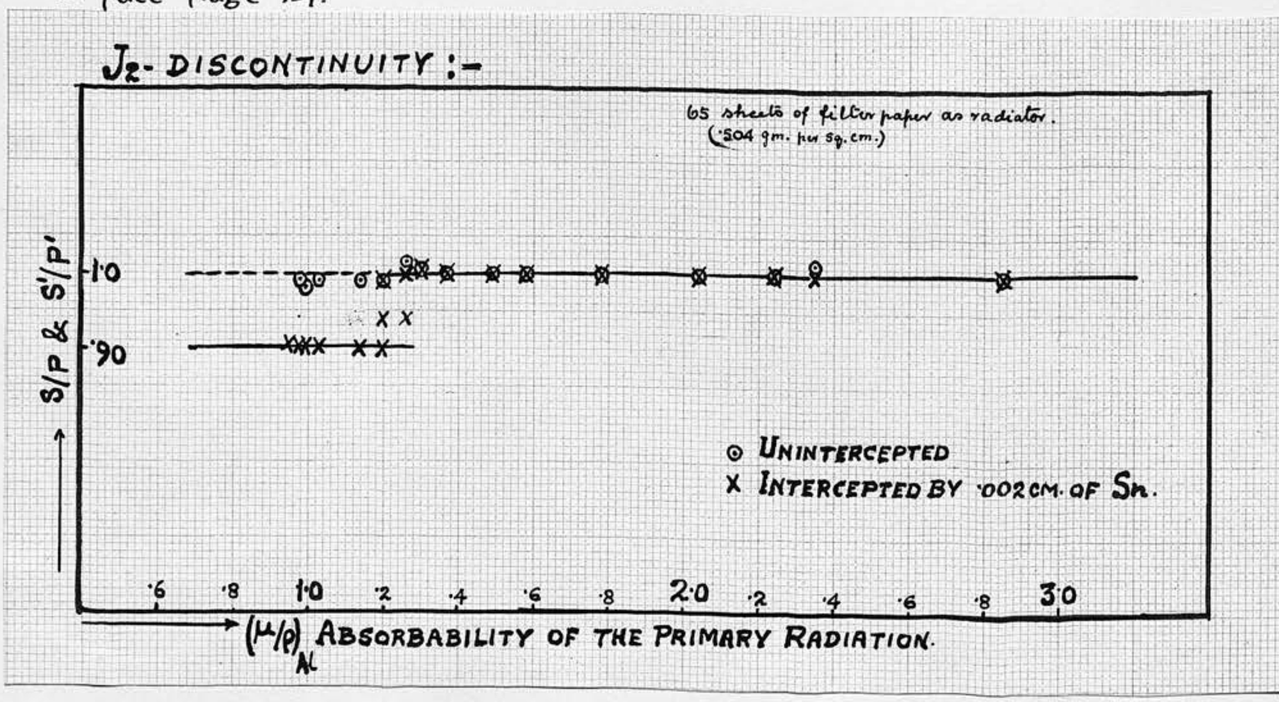

Fig. 8.

See table V

scattered beam which behaves in an anomalous way in transmission through matter. The following results will show that the transformation observed in these experiments is but one instance of a much more general phenomenon - the J-phenomenon - and is quite independent of the process of scattering.

I. The J-transformation in various substances.

The penetrating powers of the primary radiation at which these discontinuities appear depend on the material used to intercept the primary and secondary radiations. Paper, Copper, silver, tin and gold have been used in addition to Aluminium. In tables II & III and figures 4,5 and 6 are given the results of experiments where copper and paper are compared with aluminium.

Special care was taken to see that the copper and paper cut off the same amount of radiation as the aluminium. Although this precaution does not ensure equal absorption for all the constituents of a complex radiation, a comparison of the results with equivalent amounts of paper, aluminium, copper etc. can be made with a fair amount of precision. The J_1-discontinuity in silver is shown in fig.7, the J_2-discontinuity for tin in fig.8. The results are given in tables IV & V. In the case of tin and silver it should be mentioned that, under certain conditions, the primary and secondary radiations are found equally absorbable up to the J_2-discontinuity - whereas usually the increase in the absorbability of the secondary radiation appears after the J_1-discontinuity.

These results show definitely that when the J-discontinu-:ity has occurred in the secondary radiation during transmission through one substance, it has not occurred in other substances.Thus the discontinuities for different absorbing substances appear at different absorbabilities characteristic of the material and are thus independent of scattering.

It should he noticed in this connection that the ratio S'/P' for silver was amazingly constant for a wide range of wave-lengths, including the K-absorption wave-length for silver. Testing the secondary and primary radiations separately with a sheet of silver the K-absorption was however observed within the same range.

The positions of the J-discontinuities for various absorb-:ing substances are given below in terms of mass-absorption-coeffic-:ients in Aluminium: the latter were measured from a 50 per cent absorption. The thickness of each absorbing material which was kept fixed throughout the experiment is given (in brackets) against the name of the material.

J-steps.
Critical Mass-absorption Coeffieients in Aluminium:

Absorbing Material	J_1	J_2	J_3
Filter Paper (ρx = .38 cm.)	$>$ 4.0	2.1	-
Aluminium (x = .048 cm.)	3.8	1.9	.76
Copper (x = .0012 cm.)	3.5	2.3(?)	-
Silver (x = .0021 cm.)	2.0	1.4	.9 - .7
	(From filtering expts;see p.27.)		
Tin (x = .002 cm.)	-	1.2	-

With the exception of Copper therefore, it can be generalised that the higher the atomic number the higher is the critical penetrating power for the J-discontinuities; the J_2-discontinuity in Copper appears for a slightly softer beam than that in Aluminium. It seems extremely probable that the critical absorbabilities corresponding to the discontinuities are intimately connected with the electronic distribution in the atom, especially for heavier elements.

II. <u>Unmodified Secondary X-radiation - modified by filtering:</u>

(a) The J-absorption discontinuities are also obtained when the average penetrating power of a heterogeneous radiation is increased by the process of filtering. This can be very clearly shown by keeping the primary radiation unchanged and gradually increasing the thickness of the absorbing sheets placed in the paths of both primary and secondary radiations, the thickness being the same in the two beams, When the radiation is more absorbable than the critical value for the J_1-discontinuity, the ratio S'/P' is found exactly equal to S/P for thin absorbers; but when the thickness of the intercepting sheets is such that the critical absorbability is reached by the process of elimination of the softer constituents, a sudden drop in the ratio S'/P' is observed. After the discontinuity the ratio S'/P' <u>either</u> falls off gradually with increasing thickness of the absorbing substance <u>or</u> keeps constant. When the filtering is carried further and the hardness of the beam is passed through other critical regions, further discontinuities are also noticed

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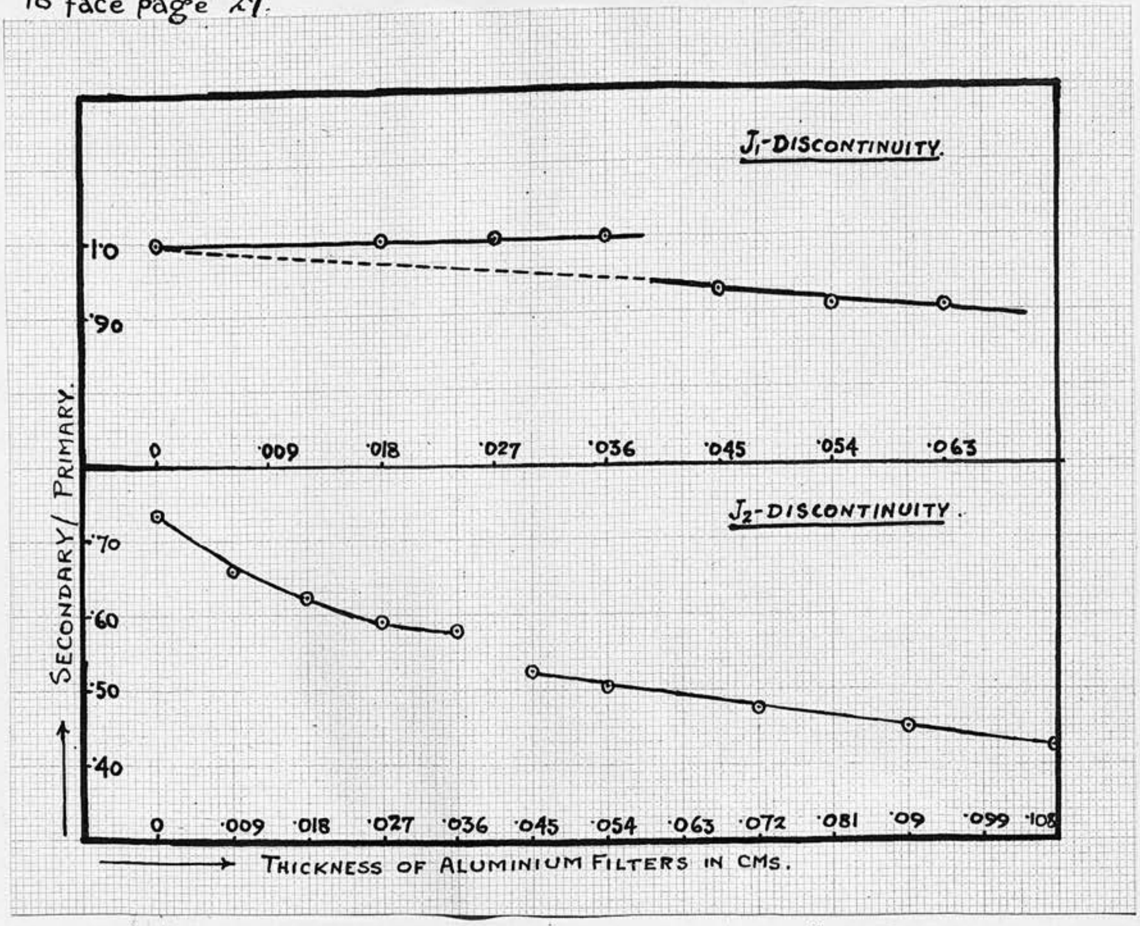

FIG. 9(a).

SEE TABLE VI.

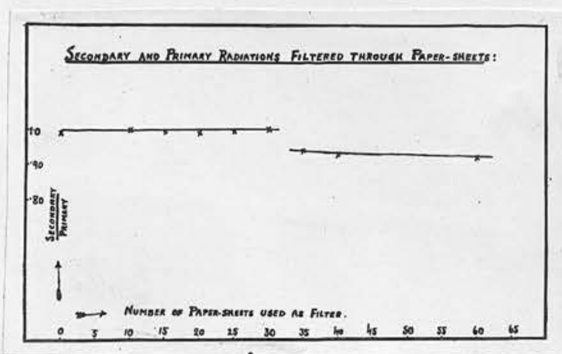

FIG. 9(b).

SEE TABLE VII

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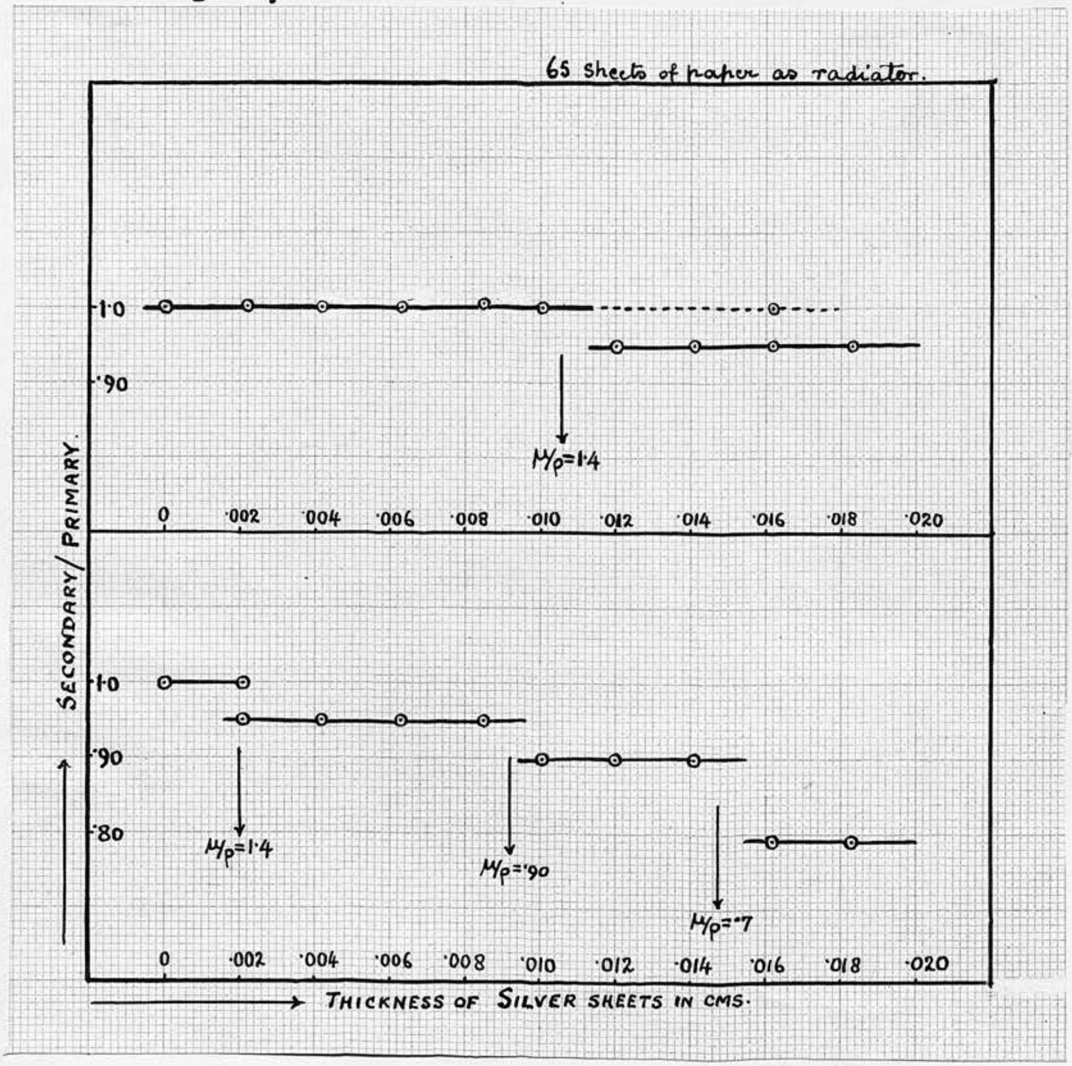

SEE TABLE VIII

FIG. 10.

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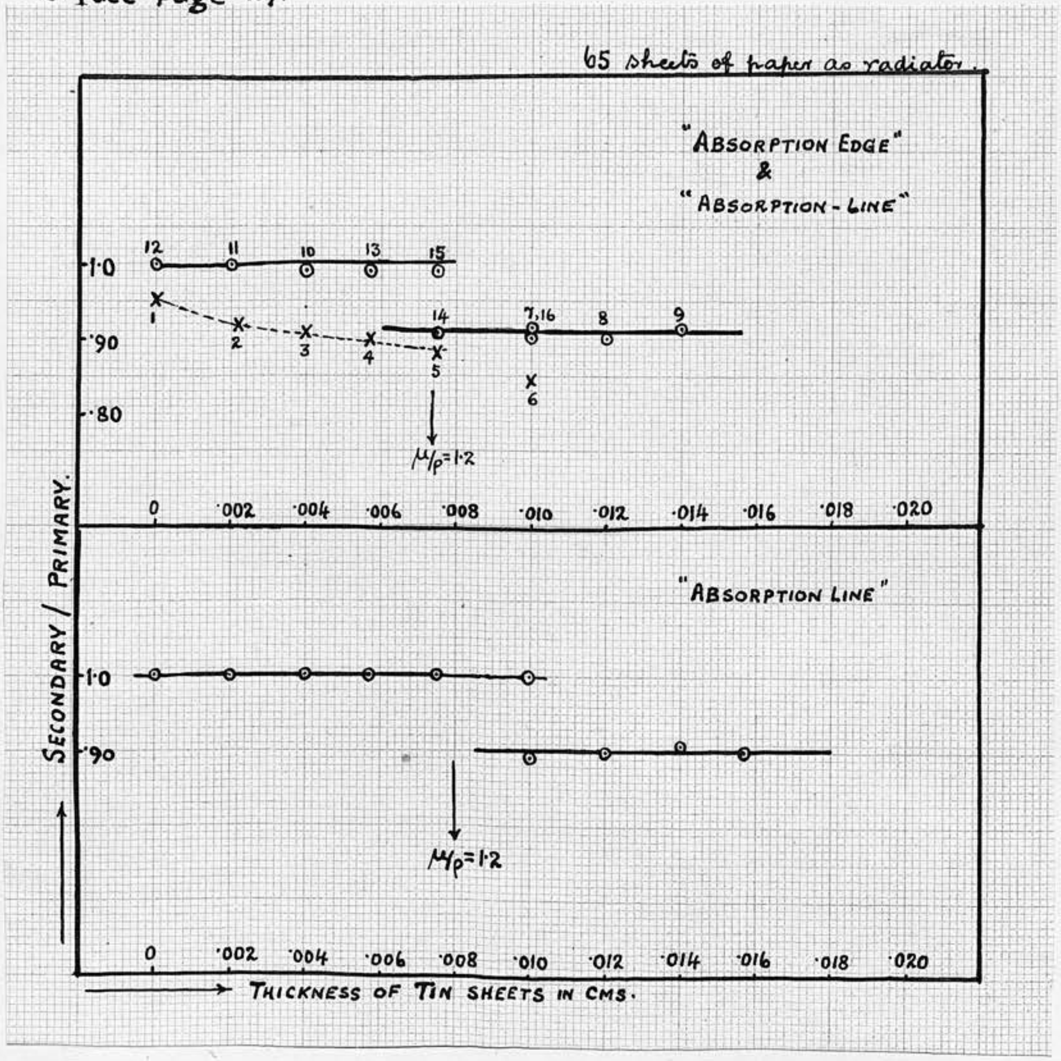


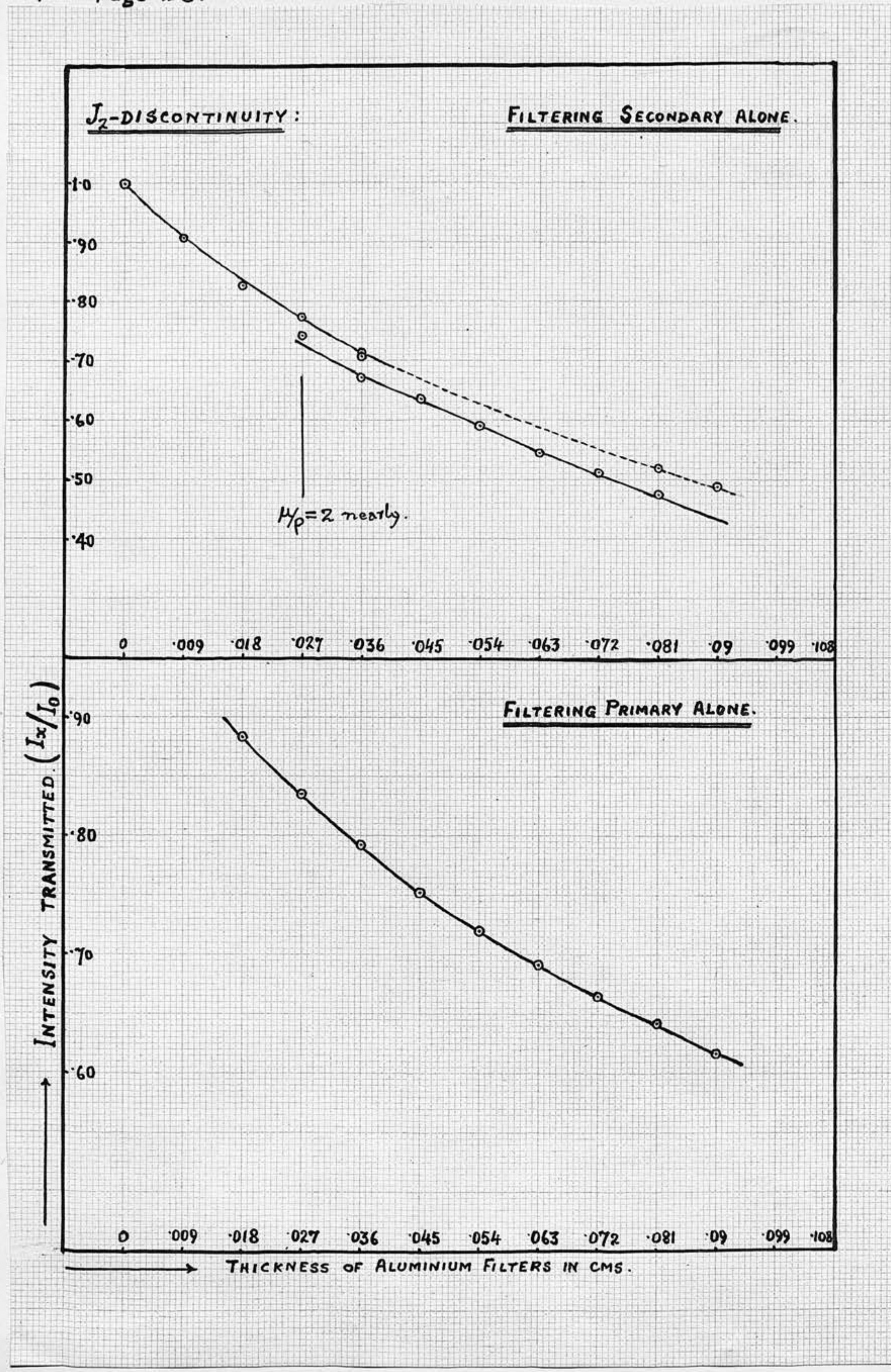
FIG. 11.

SEE TABLE IX.

in the form of sudden drops in the ratio. In the case of paper, aluminium, and copper as filtering substances, the first alternative holds, namely:- a gradual decrease in the ratio S'/P' with the increasing thickness of filters after the J-transformation. This is illustrated in figs. 9(a) & 9(b), Tables VI & VII give the actual experimental results. With silver as filtering substance, however, the second alternative holds, so that when we plot S'/P' against the thickness x of the silver sheets - there are different horizontal lines in echelon. This is shown in fig.10. (See table VIII). Tin shows <u>either</u> of these features (see fig 11 and tables IX).

Whatever may be the nature of the J-transformation - a discussion of which is given later - the experiments described above show very clearly that a scattered radiation is "modified" by the J-phenomenon which takes place in the filtering substance and independently of the process of scattering.

(b) The same modification of the scattered radiation by filtering can be shown in a similar set of experiments in which the fraction I_x/I_0 of the secondary radiation transmitted through an increasing thickness of absorbing sheets is measured. The "unintercepted" primary beam is here taken as the standard. The "intensity" of the secondary radiation as measured by the ionisation produced in SO_2 is found to diminish quite regularly with the thickness of the aluminium sheets up to a certain thickness, at which there is a sudden decrease in the intensity. At this thickness (which depends on the absorbability of the



FIGS. 12(a) & 12(b).

SEE TABLE X.

unfiltered radiation from the X-ray tube) the heterogeneous radiation passes through the critical penetrating power for the J-discontinuity and the result is a sudden decrease in the fraction of the secondary radiation transmitted. The importance of this result lies in the fact that this is the most direct evidence that the J-transformation observed is, in these experiments at least, associated with the <u>secondary</u> X-radiation and <u>not</u> with the primary. This is illustrated in figs.12(a) & 12(b); Fig.12(a) shows the J-absorption ~~rise~~ in the secondary radiation, when the heterogeneous beam is hardened by gradual filtering, up to the critical penetrating power for aluminium viz., $(\frac{\mu}{\rho})_{Al} = 1.9$. The regular absorption curve over the same range with the primary radiation is shown in fig. 12(b) (For experimental results see tables X).

III. <u>The Dependence of the Critical absorbability for the J-transformation on the thickness of the Absorbers:</u>

The critical absorbability at which a J-discontinuity is observed in the curve for S'/P' plotted against various wave-lengths depends upon the thickness of the absorbing sheets intercepting both the primary and secondary beams. When thick intercepting sheets are used, the change appears earlier (i.e. at a longer wavelength) than with thin sheets. This is in complete agreement with what we know about the J-phenomenon; for, when a thick absorbing sheet is employed, the first few layers bring the heterogeneous X-radiation to the critical value for the J-phenomenon and the later layers precipitate the change in absorption; whereas the

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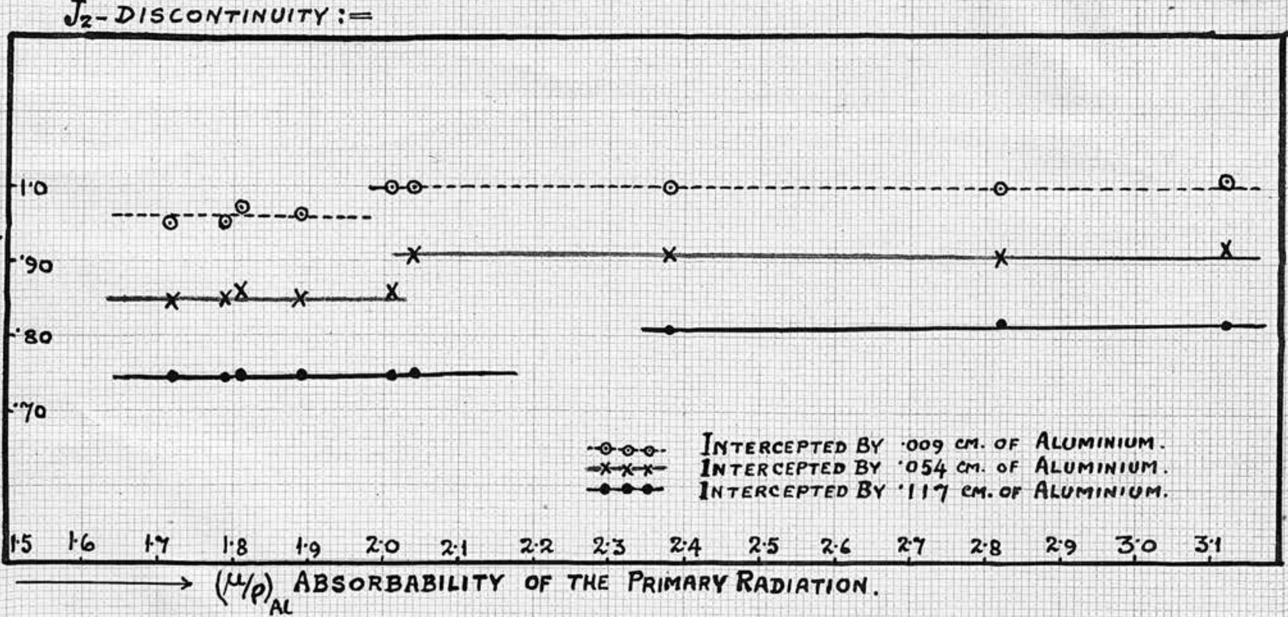

FIG. 13.

SEE TABLE XI

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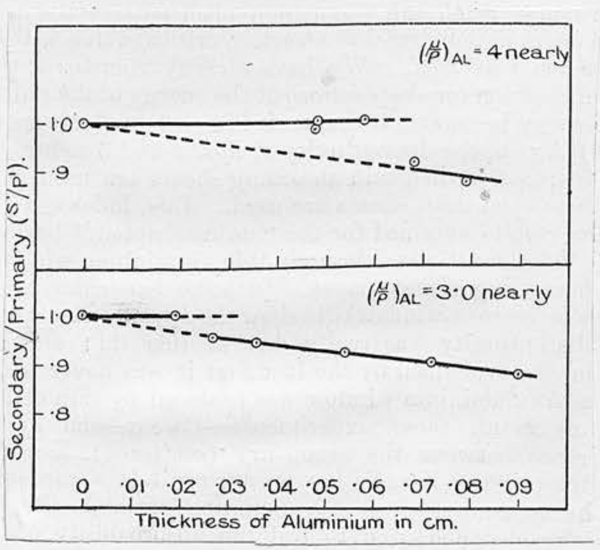

FIG. 14.

SEE TABLE XII.

thin sheets do not sufficiently change the average absorption coefficient beyond the critical point to show the discontinuity. To reach the critical point in the latter case, the radiation employed should be harder than in the case with the thick absorbing sheet. Fig.13 illustrates this with the J_2-discontinuity. In table XI are given the experimental results. This shift of position of a J-discontinuity with the thickness of the intercepting sheets, is most clearly shown by the more direct experiments described in Section II. When the radiation has the same absorbability as, or even less than that for the critical value for the J_1-discontinuity, thin filters do not show any difference between the two ratios S'/P' and S/P; but as soon as the filters are sufficiently thick to bring the radiation to the critical penetrating power, a sudden difference appears. Thus, when the radiation is "softened", the filtering has to proceed a little further before the critical absorbability is reached, and when "hardened" the discontinuity appears earlier in the filtering process. The next set of experiments will illustrate how the positions of the J-discontinuities are perfectly under control.

IV. The Magnitude of the J-Absorption.

The magnitude of the sudden fall in the ratio S'/P', at least for paper, aluminium, copper, tin and gold, generally depends on the thickness of the absorbing substances already traversed before the appearance of the discontinuity. Thus, when the X-ray tube was comparatively hard and only a few sheets of the absorbing substance were necessary to bring the secondary

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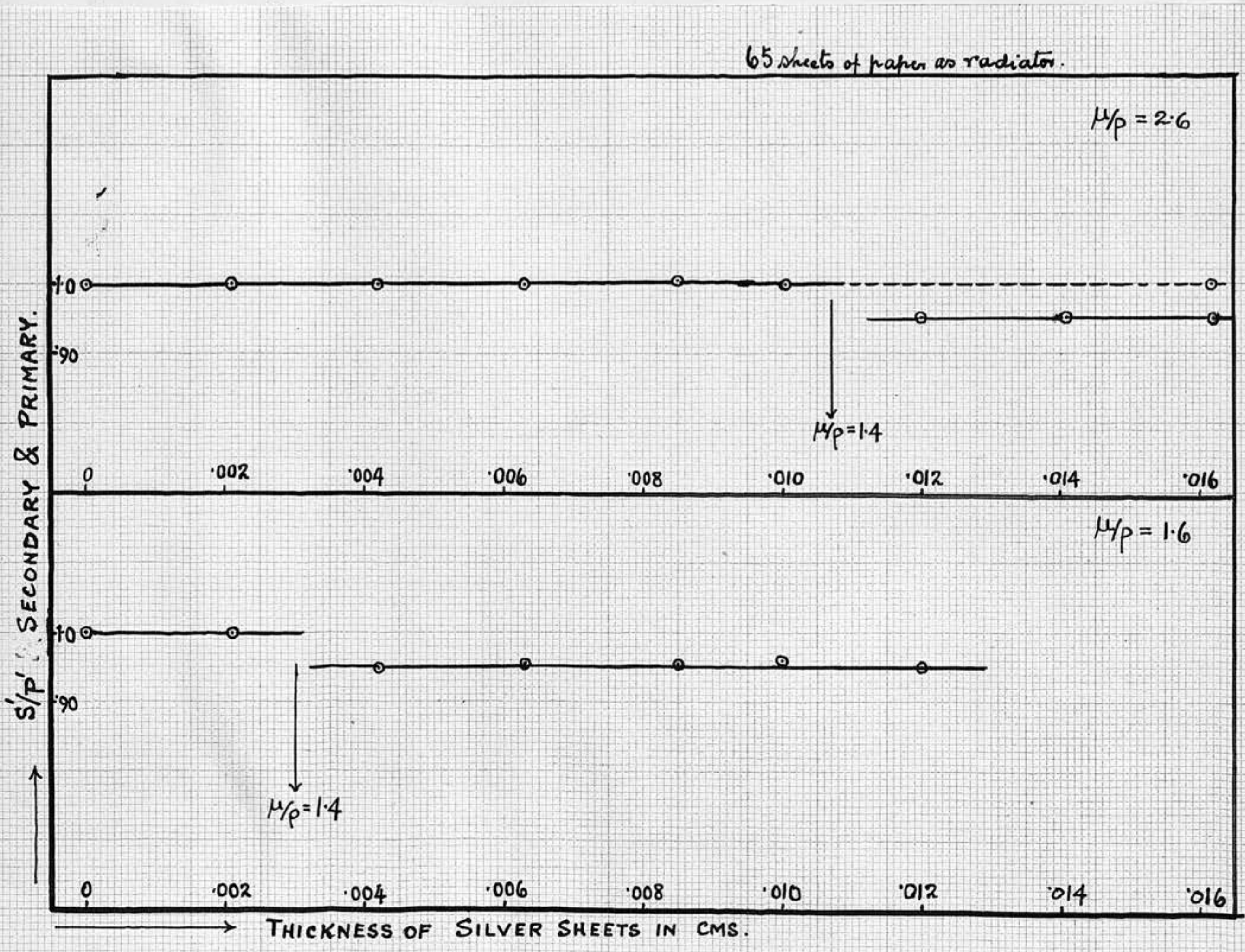

FIGS. 15(a) & 15(b)

SEE TABLE XIII

radiation to its critical penetrating power, the drop in the value of S'/P' at the point of the discontinuity was small whereas, when a thicker sheet was necessary to produce the J-discontinuity, the magnitude of the drop in the ratio S'/P' was proportionately larger. This is shown in fig.14. Results are given in table XII. In the case when the discontinuity appeared after the sixth sheet of aluminium, the magnitude of the drop in the ratio of S'/P' was proportionately larger than when the discontinuity occurred after the second sheet as in the other case. This is also revealed in the experiments where the ratio of ionisations produced by the primary and secondary radiations, with and without similar sheets of absorbing substance in the path of each beam, is measured for various wave-lengths. The difference in level between the horizontal line in these experiments for the "intercepted" ratio S'/P' after the J_1-discontinuity and that for the "unintercepted" ratio S/P clearly depends on the thickness of the intercepting sheets placed in the path of both the beams. (See fig.13 table XI).

Under other conditions however, it appears that the magnitude of the J-absorption does not depend on the thickness of the absorbing material. A typical example is shown by silver. In fig. 15a where the J-discontinuity appeared after the sixth sheet of silver, the magnitude of the drop in the ratio of S'/P' was exactly the same as in fig.15b, where the discontinuity occurred after the second sheet (See table XIII).

The same also holds for tin, although in other experiments, under apparently identical conditions, it has been found to behave in the same way as aluminium etc.(See fig.11 & table IX). These two distinct cases[1] correspond to the two alternatives already mentioned, viz:-

(1) The ratio of ionisations S'/P' after the discontinuity varies gradually with the thickness of the absorbing material when similar sheets are placed in the path of the primary and secondary radiations, or

(2) The ratio S'/P' is independent of the thickness of the absorbing material.

V. The J-transformation in thin substances:

The discontinuities of fig.2 appear much less frequently with thin absorbing sheets than with thick ones. The results obtained for the "unintercepted" beams gave a continuous horizontal line - even though the beams had to pass through thin aluminium windows into the measuring electroscopes. In some experiments , these thin aluminium windows did give rise to the J_2-discontinuity. That the discontinuity was really due to this thin aluminium window was substantiated by the fact that it was never observed when the aluminium window was

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(1). In the experiments of Barkla and Mackenzie(Phil.Mag.Feb.1926) on radiations scattered at different angles, there also appeared these two alternative cases; (1) when the ratio of ionisations by the two beams varied with the thickness of the filters and (2) when the ratio was independent of the thickness of the absorbing sheets.

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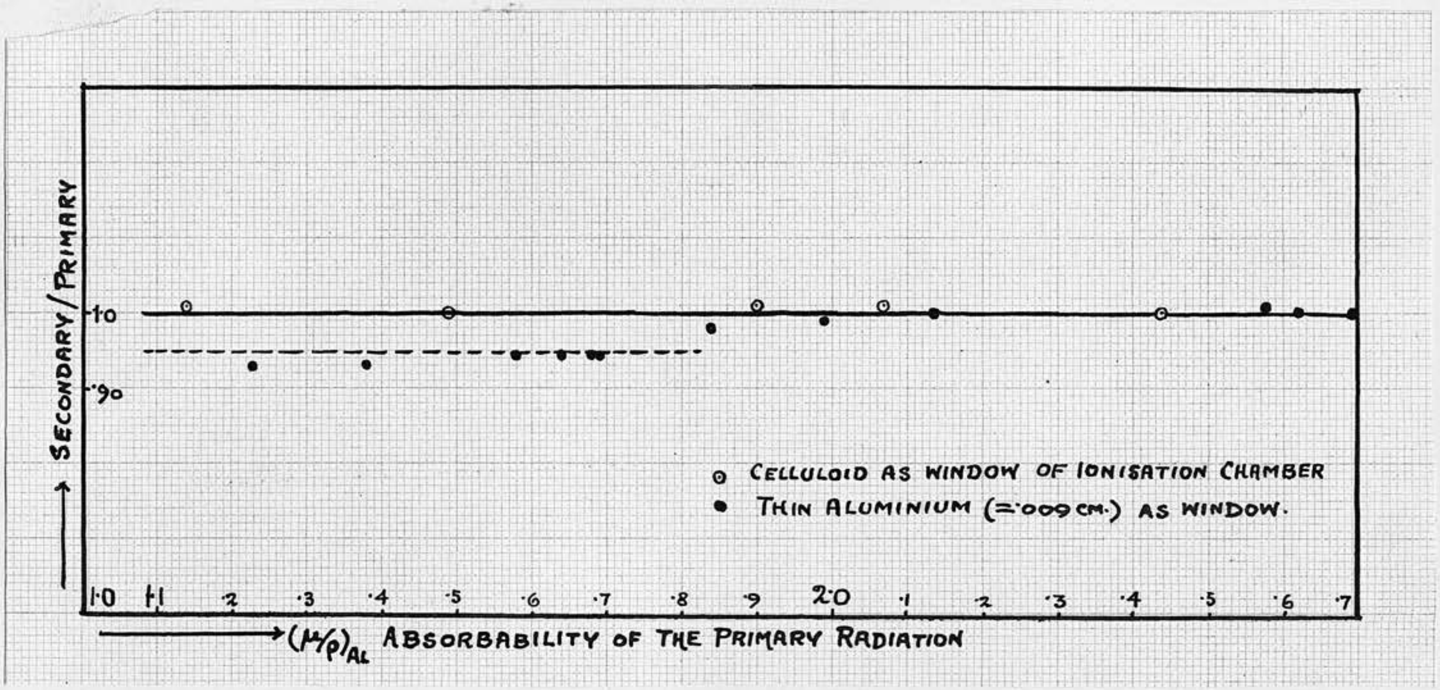

FIG. 16.

SEE TABLE XIV.

replaced by thin celluloid. Fig.16 illustrates this. (See table XIV).

From all these experiments it can be concluded that the difference between the primary and secondary radiations is only <u>apparent;</u> it is produced only as a consequence of the J-transformation of scattered X-radiation during transmission through the absorbing substance used to test the absorbability of these radiations. The transformation in a particular absorbing material takes place at a definite absorbability characteristic of the material. Apart from this transformation, distinctly associated with the intercepting sheets, there is not the slightest difference between the primary and secondary radiations, as observed in the experiments described above.

<u>Case B</u>.

In many experiments, the difference which, under the conditions of the experiments described in Case A, is observed to occur between primary and secondary radiations at particular absorbabilities of the primary, persists throughout a very wide range of wave-:lengths. As the penetrating power of a radiation is increased, it is found that the secondary radiation is more absorbable than the primary from the very beginning i.e. even for very soft, low frequency, radiations. Thus, beginning with very low frequency radiation and gradually increasing the frequency, the ratio of the ionisations produced by "intercepted" beams of primary and secondary radiations (S'/P') is found to be persistent-:ly <u>less</u> than the corresponding ratio (S/P) with "unintercepted" beams. This is illustrated in fig.17 in which the ratio for the "intercepted" beams for each absorbing substance (Aluminium, copper, tin and gold) exhibits no discontinuity either at the J_1-or the J_2 point through which it passes.[1] (See table XV.)

The persistent and constant difference in the values of S'/P' and S/P without any sign of a discontinuity over a long range of frequencies, represents the nearest approach to anything in the nature of a change in wavelength on scattering. The only conclusion which can reasonably be adopted, if these experiments in Case B are considered alone, is that there is a change in the absorbability of the radiation on scattering. The following will however, show that such a conclusion does not express the truth about the phenomena associated with a scattered X-radiation.

Let the radiation employed be supposed homogeneous; the ratio of the ionisations produced by "unintercepted" beams is then a measure of the relative intensities of secondary and primary radiations i.e.

$$\frac{S}{P} = K. \frac{I_s}{I_p}. \frac{i_2}{i_1}$$

where I_s and I_p are the intensities of the secondary and primary radiations, i_2 and i_1 are the ionisation coefficients of these radiations and K is a constant depending on the apertures used in any particular arrangement of the apparatus. The ratio S'/P' on the other hand for the "intercepted" beams is given by

(1) It might be said here that if we could extend sufficiently the range of wavelengths experimented upon, a step like the J_1-step would be observed in the region of very low frequencies.

$$\frac{S'}{P'} = \frac{K.\ I_s\ i_2\ e^{-\mu_2 x}}{I_p\ i_1\ e^{-\mu_1 x}}$$

where μ_2 and μ_1 are the absorption coefficients of the secondary and primary radiations respectively; so that

$$S'/P' \div S/P = e^{-(\mu_2-\mu_1)x}$$

This ratio of S'/P' to S/P has been found to be remarkably constant from very low to very high frequencies, the values of S'/P' and S/P lying distinctly on two horizontal lines, exactly in the same way as in Case A after the J_1-discon- :tinuity. It is also found that this ratio(S'/P' $\div$ S/P) is precisely the same in Case B as is actually observed after the J_1-discontinuity in Case A. In other words the change from S/P to S'/P' which in Case B appears to be produced in the scattering substance is exactly identical with that which is observed in Case A, to have taken place in the absorbing substance.

Thus it can be said that the process by which the difference between secondary and primary beams, is produced, is identical in the two cases A and B. In Case A we have seen that the change of character occurs distinctly outside the scattering substance, and in Case B, where the change takes place outside the range of direct experimental investigation, we must regard it as due to an identical process, not in any way, connected with the fundamental process of scattering.

The identical nature of the process by which the

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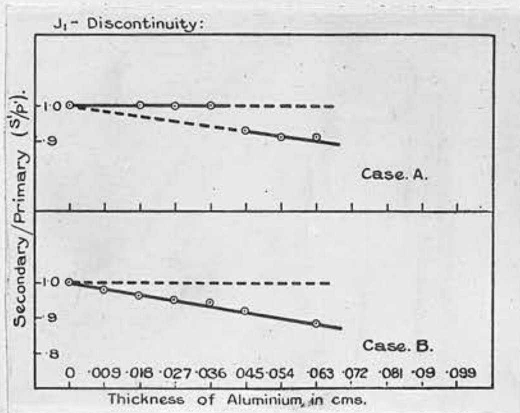

FIG. 18.

SEE TABLE XVI.

difference between the primary and secondary radiations is produced in Cases A and B is also evident from the filtering experiments where S'/P' (i.e. the ratio of the ionisations produced by the secondary and primary radiations) for a given state of the X-ray tube, is measured for various thicknesses of similar absorbing sheets placed in the paths of the secondary and primary beams. In case B this ratio S'/P' has been found to vary continuously with a thickness x of the absorbing material. Thus, the difference between the primary and secondary radiations is observed from the very beginning whereas in Case A, as we have seen, the secondary and primary beams are alike for small thicknesses, the difference only appearing after a certain thickness when the critical absorbability for the J_1-discontinuity is reached by the process of filtering a heterogeneous radiation. If we compare the curve for S'/P' plotted against the thickness x in Case A with that in case B, we see that the sloping portion to the right of the J_1-discon:tinuity in Case A is the latter portion of the line sloping comtinuously from the commencement in Case B. This is illustrated in fig 18 (See table XVI). It is evident that in Case A the difference in the secondary and primary radiations is in some way or other held up or remains latent up to a particular thickness of the absorbing material when the requisite hardness for the J_1-transformation is attained. The last layer of the absorbing sheets necessary to produce the discontinuity percipitates a change which has already been made possible by transmission through the first layers, for the magnitude of the

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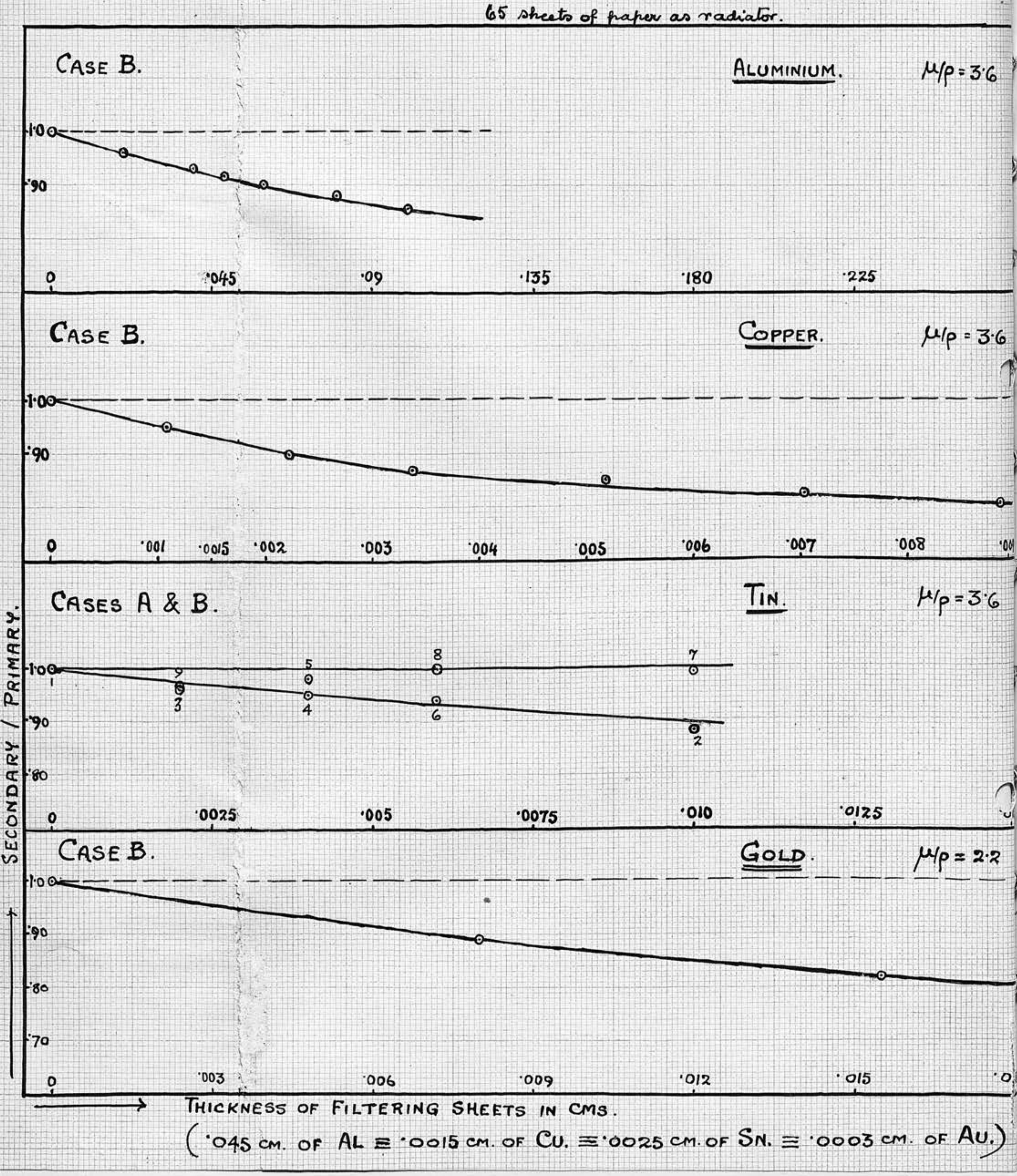

FIG. 19(a).

SEE TABLE XVII

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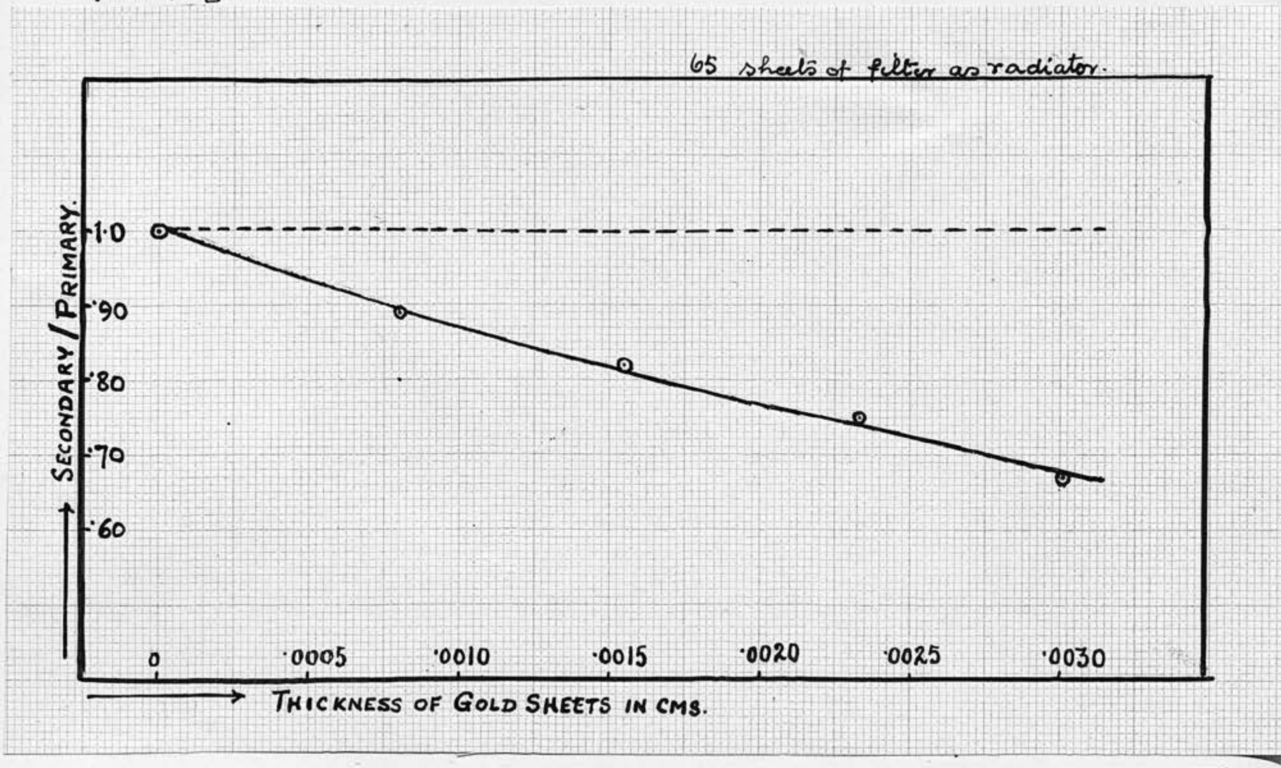

FIG. 19 (b).

SEE TABLE XVII

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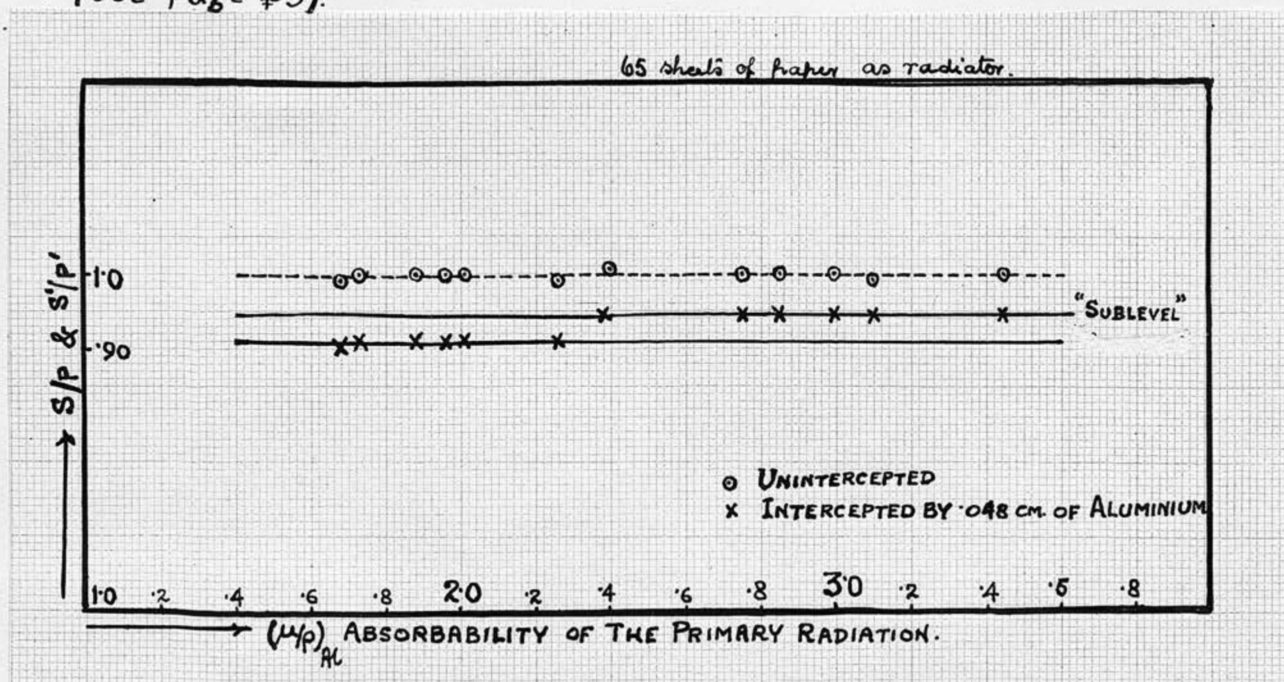

FIG. 20.

SEE TABLE XVIII

change after the J_1-discontinuity is just such as to compensate for what might, under different conditions (Case B) have taken place gradually in the absorbing substance already traversed. Curves for copper, tin and gold in these filtering experiments are given in fig.19(a) and (b) see table XVII. Superficially however, they indicate a true transformation of the radiation on scattering.

We should now record here two special results in Case B. which are worthy of consideration:

(1) In a few experiments it has been found that the difference between the penetrating powers of the primary and secondary radiations (in aluminium) is what would be expected after the J_2-discontinuity, even for soft radiations. Thus, in these experiments beginning with a soft radiation and gradually hardening it, the ratio S'/P' persistently maintains a value corresponding to the level after the J_2-discontinuity.[1]

(2) In a few experiments again, the difference between the mass-absorption-coefficients of the primary and secondary radiations in aluminium, has been found to be decidedly less than that generally obtained in Case B or after the J_1-discontinuity in Case A. This is indicated by a difference of only 5 per cent between S/P and S'/P' (the ratios of the ionisations produced by the "unintercepted" and "intercepted" radiations) whereas the difference usually observed with .048 cm. of aluminium is

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(1) It seems probable again that if we could extend sufficiently the range of wavelengths experimented upon, both J_1 and J_2 steps would appear in the region of very large wavelengths.

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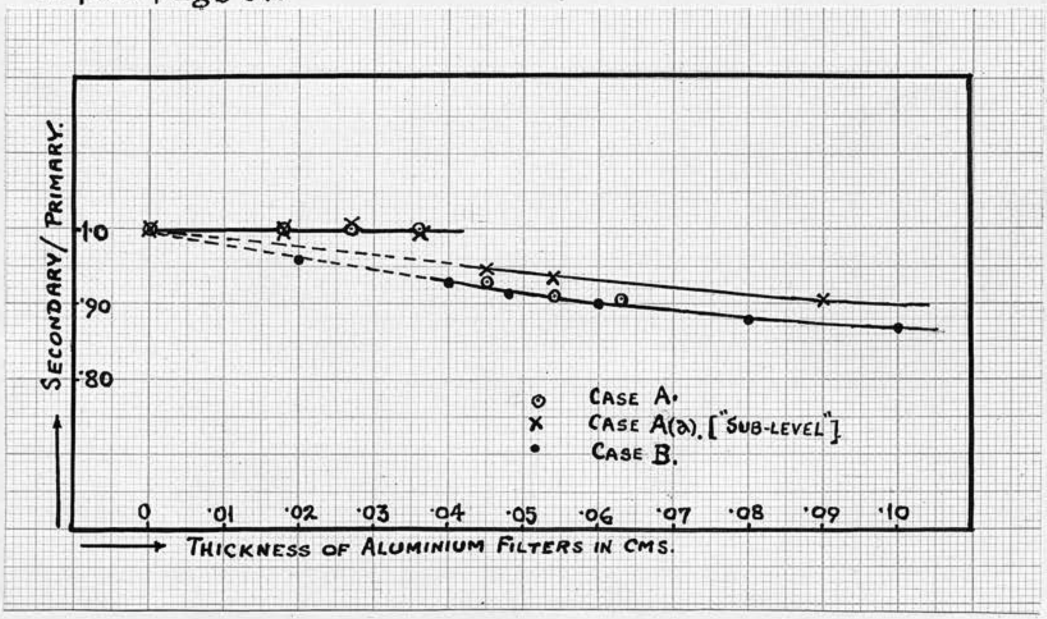

FIG. 21.

SEE TABLE XIX.

9 per cent. The difference in this case between the mass-absorption-coefficients of the primary and secondary radiations is on calculation found to be .4 approximately.

The conditions under which this is obtained appear to be very unstable as is clearly seen from the alternative fixed values of S'/P' which lie on two distinct horizontal lines over a long range of wavelengths. This is illustrated in fig,20. See table XVIII.

This case really comes under either Case A or Case B(according to whether we obtain or miss the J_1-discontinuity) the special feature being that, instead of the normal J_1-drop we get in this case only a "sub-level". We shall refer to this case of a"sub-level" as Case A(a) or Case B(a) in future. Cases A, A(a) and B are very well illustrated in fig. 21 where the values for S'/P' are plotted against the thickness x of the aluminium sheets, equal thicknesses of which are placed in the paths of both beams.(See table XIX for experimental results). The results for the three cases in fig.21 were however, obtained at quite different times.

Thus, in summing up the results of all the experiments, we can say that various alternative values of S'/P' are possible, presumably under different conditions and that when any one particular condition prevails, the ratios S'/P' is found to be remarkably constant over a long range of wavelengths. The difference between the absorbabilities of the secondary and primary radiations is therefore independent of the wavelength of the primary radiation. If however, under conditions of the experiments described in Case A, discontinu-:ities in S'/P' do appear, they occur at particular values of the mass-absorption-coefficients; so that when we plot S'/P' against the absorbability of the primary radiation, different horizontal lines are obtained. It is evident therefore, that corresponding to these horizontal lines, there are several values for the difference in the absorbabilities of the secondary and primary radiations - the difference increasing in a series of steps after each J-discontinuity.

In the following table are given the different values of $(\frac{\mu_2}{\rho}-\frac{\mu_1}{\rho})$ for each absorbing substance. The values of $(\frac{\mu_2}{\rho}-\frac{\mu_1}{\rho})$ are calculated from the fractional fall in the ratio of the ionisations due to transmission of both secondary and primary beams, through similar thicknesses of different equivalent absorbing substances. 100(S/P - S'/P') / S/P, which is the percentage fractional fall in the ratio S'/P', is also given in the table.

Absorbing substance.	$\frac{100\,(S/P - S'/P')}{S/P}$			$\frac{\mu_2}{\rho} - \frac{\mu_1}{\rho}$			Thickness of the absorbing substance
	$-J_1$	$J_1 - J_2$	$J_2 - J_3$	J_1	$J_1 - J_2$	$J_2 - J_3$	
Filter Paper	0	7	12	0	.18	.33	x = .38 cm.
Aluminium	0	9	15	0	.72	1.0	x = .048 cm.
Copper	0	7	12	0	7.0	12.0	x = .0012 cm.
Silver	0	4	8	0	1.9	3.8	x = .002 cm.
Tin	0	3to 4	9	0	2.7	6.4	x = .002 cm.
Gold	0	9	-	0	6.1	-	x = .0008 cm.

The Alternative levels of X-ray activity:

It should be emphasised here that Cases A and B are alternative. The alternative nature of these could be illustrated by collecting all the observations, good and indifferent, obtained at various times with different experimental arrangements and showing their distribution.

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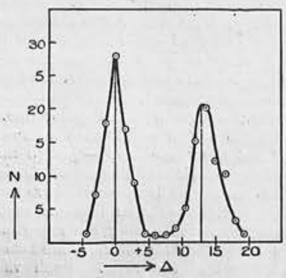

Ordinate: Number of observations within the range of $\pm 0{\cdot}75$ per cent. of abscissa.

Abscissa: Percentage change of absorption-coefficient.

Displacement of $\left(\frac{\mu}{\rho}\right) = 13$ per cent. when $\left(\frac{\mu}{\rho}\right) = 5{\cdot}2$ or $5{\cdot}3$ average, *i.e.* Mo K_α.

FIG. 22.

SEE TABLE XX

To face page 40.

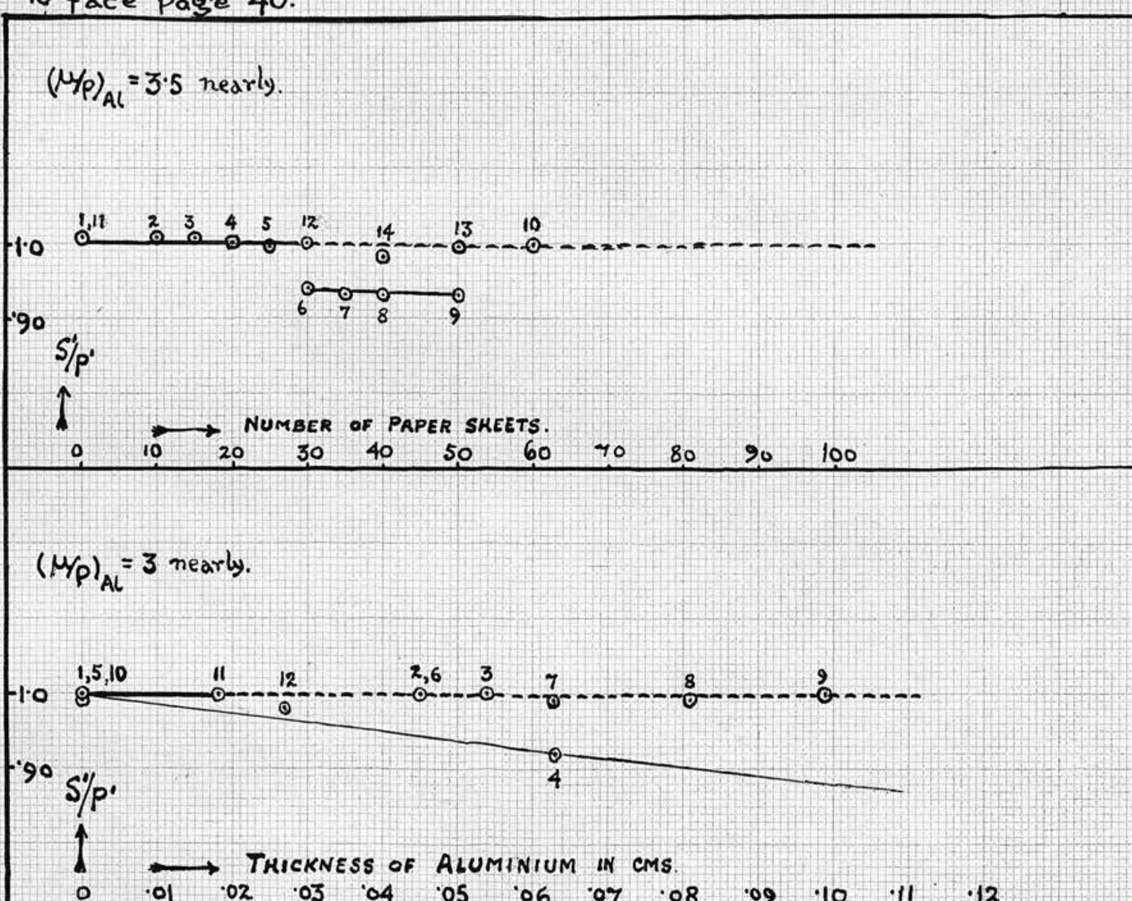

FIG. 23.

SEE TABLE XXI

Fig 22 shows the number of measurements plotted against the observed difference between the absorption coefficients of the secondary and primary radiation when the primary had an average absorption coefficient $(\frac{\mu}{\rho})_{Al}$ in the neighbourhood of 5.2, which is the mass-absorption coefficient of Mo. K-radiation in Aluminium (See table XX). The distribution curve clearly shows two peaks, one corresponding to an absolutely unchanged radiation $(\frac{\mu_2}{\rho} - \frac{\mu_1}{\rho} = 0)$ and the other corresponding to a definite change in the value of the "absorption coefficient" of 13 per cent (- $(\frac{\mu_2}{\rho} - \frac{\mu_1}{\rho} = .72)$. [If the number of observations was more extensive and ranged over a longer time, two more "peaks" would have appeared in the distribution curve, one corresponding to the case A(a)(sub-level) and the other to some experiments in Case B where a "double-drop" in the ratio S'/P' has been observed even for very soft radiations. As these cases are only very few, they have not been included in the distribution curve.] (1)

The two "peaks" shown in the distribution curve are very suggestive of the intensity curve with two similar "peaks" obtained in one experiment by Compton and others. It should be pointed out that in our experiments, the "peaks" were produced

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(1) It is needless to say that fig.22 shows the results of our methods at their worst. It is only when we have a series of observations with one form of apparatus, that best results are expected. Then the two spectral lines are simply two vertical lines completely separated by a gap several times the width of either line. The horizontal lines of fig 3 are in reality such spectral lines - the "modified" and the "unmodified" - though the method of drawing shows them horizontal, instead of vertical. There were a few observations which were found to lie between the two "peaks"; in most of such cases it was seen that a change actually occurred during the experiment, so that the final readings were intermediate between the two instantaneous values of the ratio. The result of such a change of the critical condition during the experiment in general accounts for the width of the two "peaks,"

not simaltaneously but only alternatively and in addition the "modified" peak in our experiments is the effect of a transformation entirely independent of the scattering process. Thus there are definite alternative states of the scattered X-radiation giving rise to alternative levels of absorption in the substance used for testing its absorbability; the condition determining these levels of activity are not only the wavelength of a radiation and the atomic number of the absorbing substance, but also something more which has not yet been identified.

It has already been shown that all the values of the ratio S'/P' fall on four continuous horizontal lines, the three steps being marked J_1, J_2, and J_3. If the "sub-level" in Case A(a) is taken into account, there are altogether five different levels of activity in aluminium within the range of our observations. Let us call the different levels α, β, γ, δ and ϵ. (See fig.29). Thus according to our nomenclature the primary radiation is supposed to be always in state "α" ; and when the scattered radiation is in the same state, there is no difference observed between the scattered and primary X-radiations. The difference between them varies according as the scattered radiation is in state β, γ, δ, or ϵ.

It should be mentioned here that in only two cases out of hundreds of experiments was there an indication of the primary radiation changing its state i.e. undergoing the J-transformation. This is illustrated in fig 23 (see table XXI). These results can equally well be taken to mean that the scattered radiation continues to be in state "α", for short

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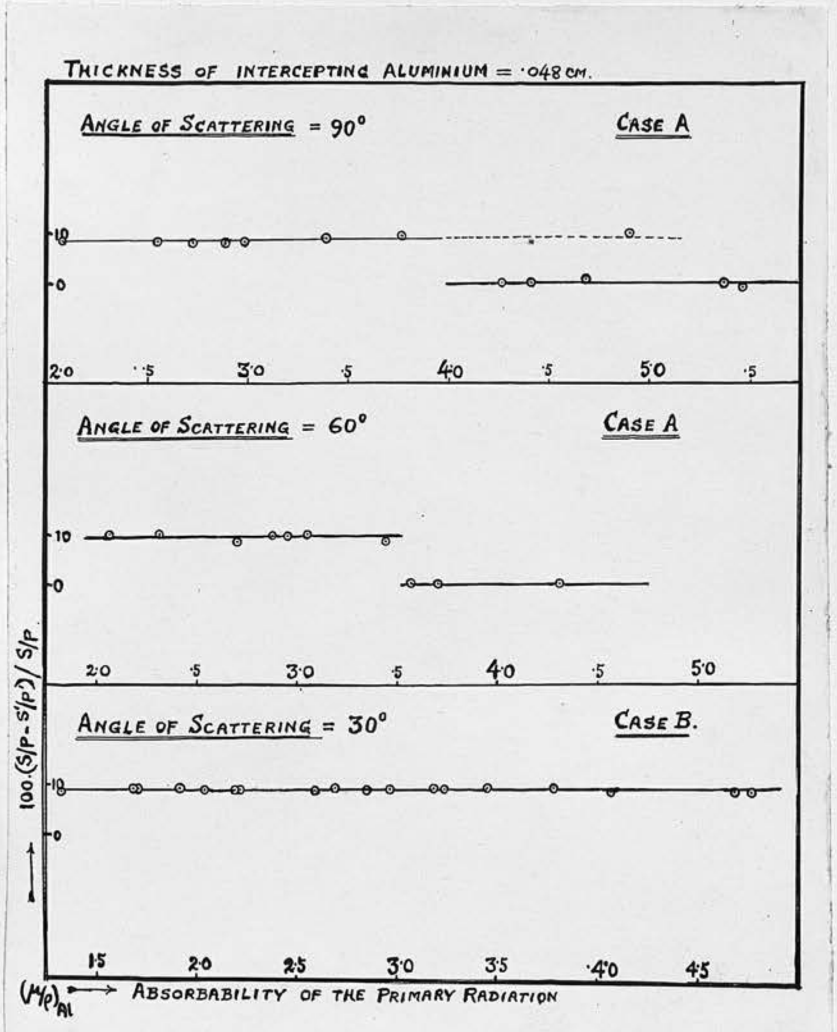

FIG. 24.

SEE TABLE XXII.

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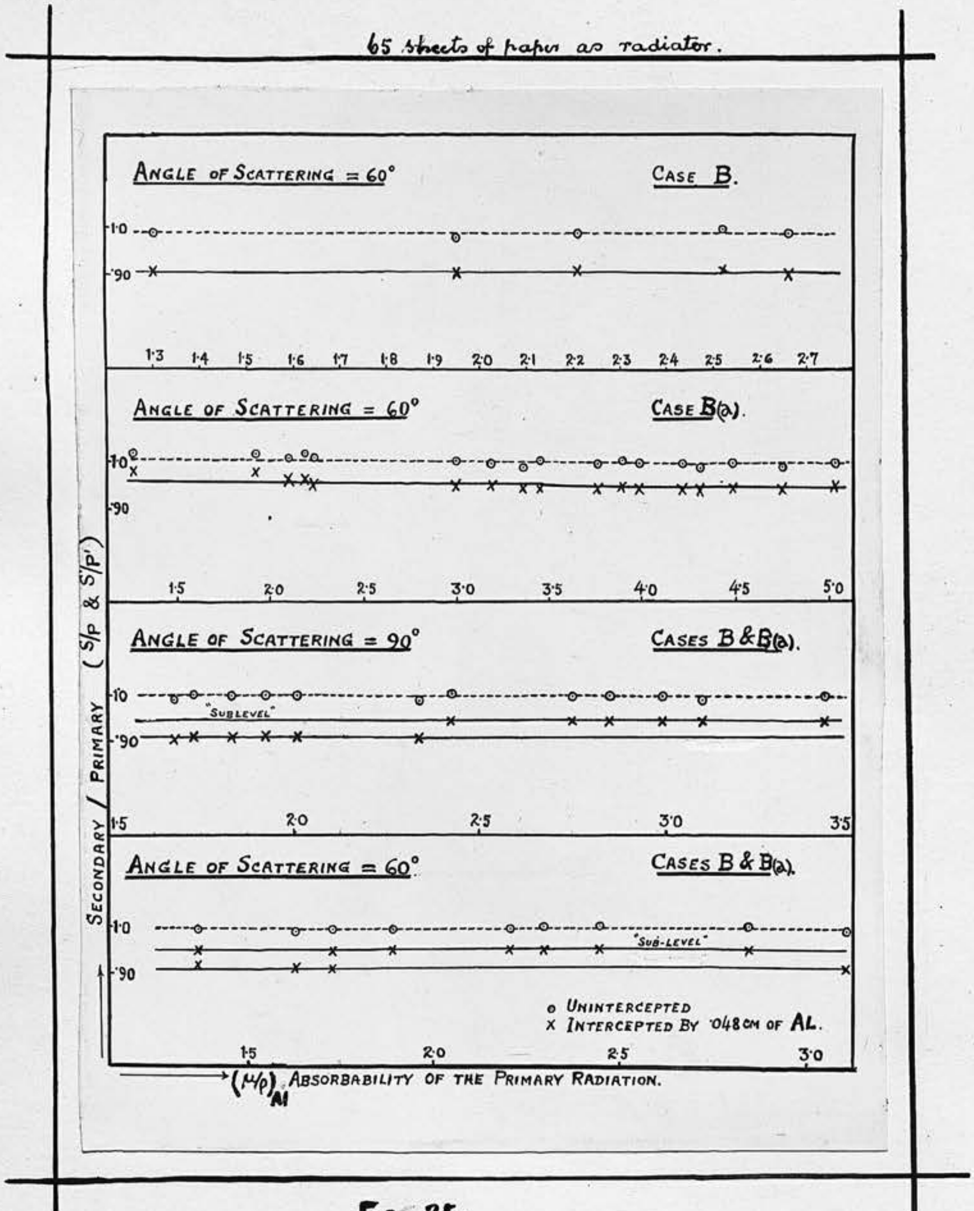

FIG. 25.

SEE TABLES XXIII & XXIV.

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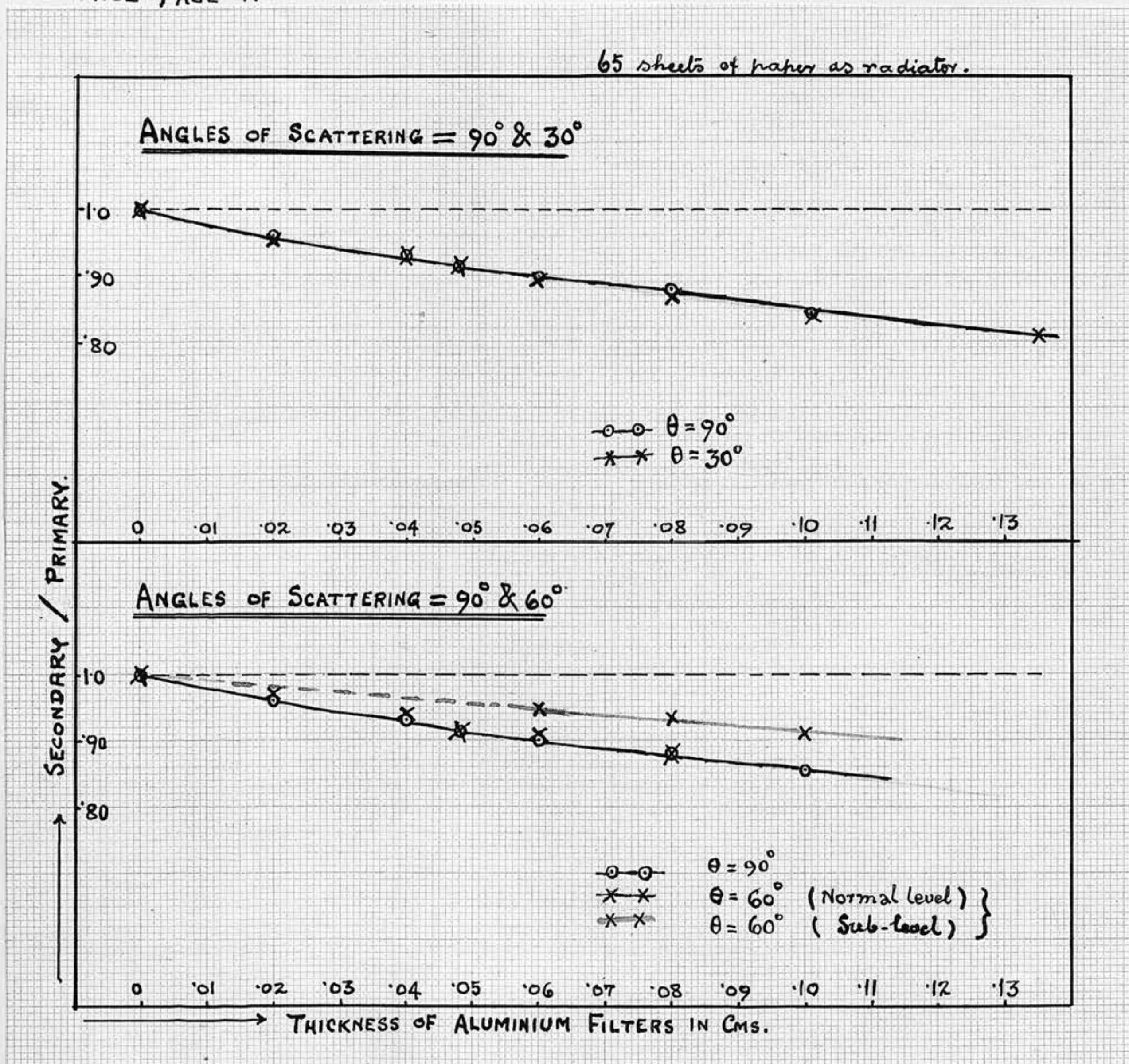

FIG. 26.

SEE TABLE XXV

wavelengths; but, in view of Barkla's experiments on the J-discontinuity with primary X-radiations, it appears more reasonable to conclude that the prolonged equality observed between the primary and secondary radiations is due to the fact that both primary and secondary radiations have changed their states.

Scattering at different angles;

X-radiations scattered from the emergent side of the radiator at angles 30° and 60° to the primary radiation were examined in a way similar to those scattered at 90°. In each case the sheets of filter paper which were used as the scattering substance were placed in a position so that they made equal angles with the primary and secondary radiations. In both sets of experiments (i.e. in experiments where the ratios S'/P' and S/P were measured for various wavelengths, as well as in the filtering experiments, where the measurement of S'/P' was made for gradually increasing thickness of similar sheets of the absorbing substance placed in the path of both beams) the variation of the angle of scattering does not appear to have any influence on the effect of the J-transformation. Using aluminium as an absorbing substance Cases A, A(a) and B appear to take place at 60° in much the same way as at 90°. At 30° Case A(a) did not appear. The typical results are given in tables XXII to XXV and figs. 24to 26 show them graphically.

It should be stated here that the comparison of results at three different angles was made in more than twenty series of observations. The J-effects at different angles could be compared very easily with one another, simply by swinging round the secondary ionisation chamber and adjusting the radiator at the same time to make it equally inclined to the two beams. The aperture used for the incident primary beam was usually a very small circular one, 1.6 cm. in diameter with a directing tube of lead attached to it. This served to cut out most effectively the stray radiations from the glass of the X-ray tube, especially when the angles of scattering were small. At 30° a vertical slit 2 to 4 mm.wide was sometimes used with the directing tube of lead; the results were exactly the same as those when a small circular aperture 1.6 cm. in diameter was used. Great care was taken to cut off stray radiations as much as possible at 30°.

Although results obtained at different angles are substantially the same, there are certain features which are worth while now to consider:

(1) The "sub-level" which in Case A(a) is found with aluminium appears to be more frequent at 60° than at 90°. If we consider Mo. K - radiations, the change in the absorbability of the secondary radiation scattered at 90°, if any, is generally 13 per cent, whereas at 60° the change which occurs more frequently, that of only 7 per cent, It must, however, be emphasised that the change of 13 per cent at 60° and the change of 7 per cent at 90° are also both observed, when aluminium is used as the testing material. (See figs,25 & 26).

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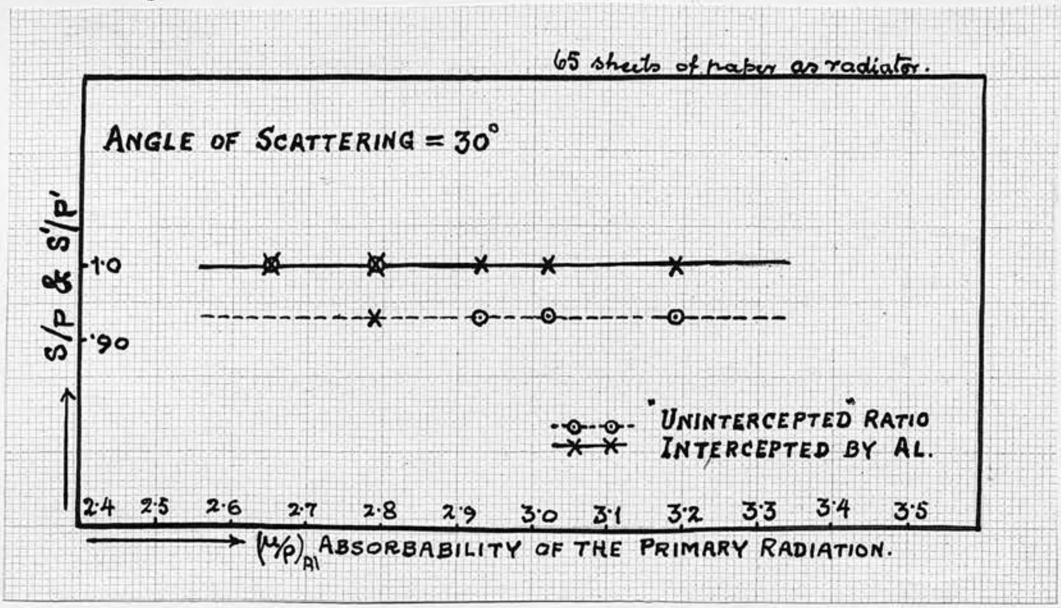

FIG. 27.

SEE TABLE XXVI

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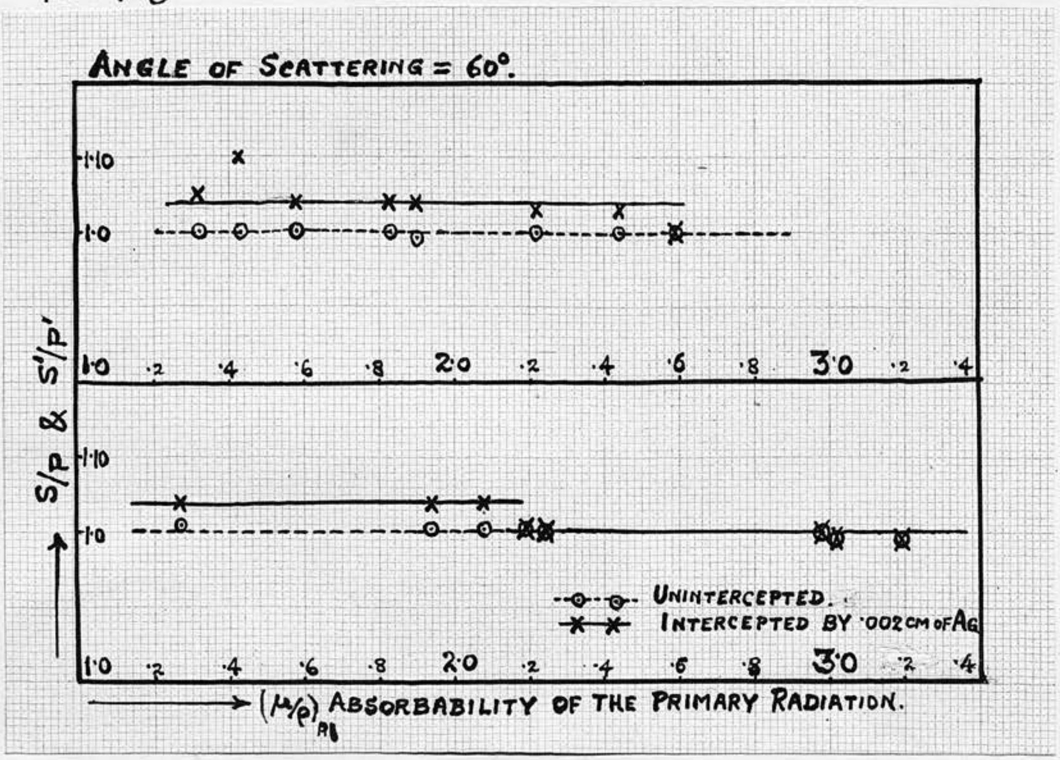

FIG. 28. (a) & (b).

SEE TABLE XXVII

(2) The "sub-level" is in no case observed at 30°. In the neighbourhood of Mo. K-radiation ($\mu/\rho_{Al} = 5.2$) the difference, if any, is found to be 13 per cent - the same as is observed at 90°. (See fig.24).

(3) The position of the J-discontinuity appears to have a tendency to shift slightly towards the short wavelength side for smaller angles of scattering. (See fig.24).

(4) In one series of observations at 30°, while testing the radiations with aluminium, the secondary beams was found to be <u>either</u> exactly like the primary <u>or</u> distinctly <u>harder</u> than the primary. The range of waveltngths over which these observations were made is, however, limited. (From $\mu/\rho = 2.4$ to $\mu/\rho = 3.4$). Thus, while plotting the ratios S'/P' and S/P, as usual, against the absorbability of the primary radiation, there were two distinct horizontal lines; the values of S/P were <u>either</u> on the upper line <u>or</u> on the lower, whereas the values of S'/P' were always (except for one observation) on the upper line. (See fig 27 and table XXVI.). It was thought that this extraordinary result was due to the primary radiation having changed its state for some reason or other. It was practically certain that this was not the case for immediately afterwards the secondary radiation at 90° was examined, and was found to be more absorbable than the primary by the usual amount.

It does not seem improbable that there is stil another <u>state</u> for scattered X-radiations giving rise to another level of activity, as a result of which the primary radiation appears more absorbable than the secondary radiation .

(5) This extraordinary result was observed more than once with silver as the testing material when the angle of scattering was 60° as well as 90°. The thickness of silver (.002 cm.) used was equivalent to .05 cm. of aluminium approximately, before the K-absorption edge of silver appeared. The ratio S'/P' found was <u>either</u> exactly equal to <u>or</u> distinctly higher than S/P. The amount by which S'/P' rose higher than S/P was exactly the same as the amount by which it normally drops below S/P. This is illustrated in figs.28(a) & (b) (See table XXVII.)

It is certain that the conditions under which the primary beam appeared softer than the secondary, prevailed also in the experiments of J.A.Gray[1] of the relative absorption of the primary and secondary radiations by silver. In Gray's experiments, the average frequency in the primary beam was a little greater than the characteristic absorption frequency of silver; and he found that the primary beam was softer than the secondary. This result he interpreted as being due to a real change of wavelength on scattering. The scattered radiation, being of a longer wavelength, could not excite the K-characteristic radiation in silver, whereas the primary radiation did. This interpretation is not compatible with our results; for we have obtained an exact equality between the absorption of the primary

(1) J.A.Gray, trans. Roy,Soc. Canada, Sec.3, 1922.

and secondary radiations by the same thickness of silver or tin over a long range of wavelengths; and whenever the difference has appeared, as in Case B, the ratio S'/P' in both cases has been found to remain remarkably constant over a wide range of frequencies, ($\mu/\rho_{Al} = 1.3$ to $\mu/\rho_{Al} = 5.0$). If Gray's interpretation were correct, there should have been a rise in S'/P' over a small range in the region of the K-absorption for silver or tin. No such effect was observed within the range of our observations - although within the same range, the K-absorption for silver (or tin) exhibited itself markedly when each beam was tested separately. The theory of wavelength change on scattering will be discussed in a separate section in relation to the results of our absorption experiments.

It is interesting to notice that our absorption experiments with scattered X-radiations at different angles, agree almost perfectly with the experiments of Barkla and Mackenzie[1] showing the J-discontinuities in Aluminium. Their experiments show that <u>either</u> there is an exact equality of the penetrating powers of two beams, one scattered at 60° and the other at 120° <u>or</u> there is a difference between the two. The absorption of the two scattered beams in their experiments is studied by placing an increasing number of similar aluminium sheets in the paths of both beams. The constancy of the ratio of ionisations (I_1/I_2) produced by the two beams from the very beginning, shows that both the beams must be in the same <u>state</u>. The discontinuities appear, when one beam continues to be in the

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(1) Barkla and Mackenzie, Phil.Mag.Feb.1926.

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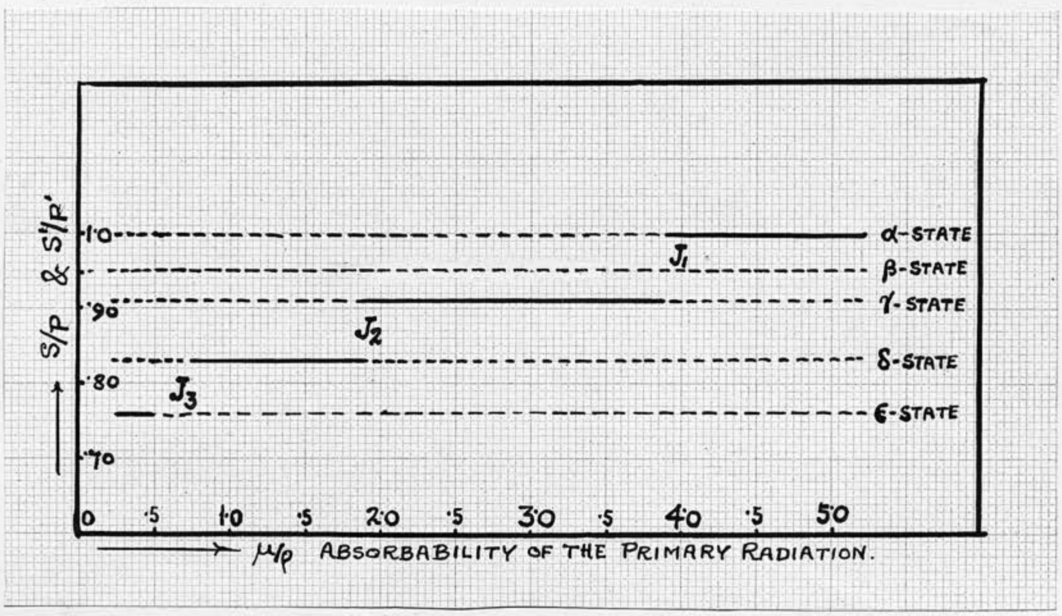

FIG. 29.

same state and the other changes from this to another. In the alternative case, when the ratio of ionisations (I_1/I_2) shows a continuous diminution with the thickness of the aluminium filters, there are two distinct sets of results as this continuous diminution may be either (1) rapid or (2) slow. A simple calculation will show that if $\frac{\mu_2}{\rho}$ be the mass-absorption-coefficient of one beam and $\frac{\mu_1}{\rho}$ that of the other, in one case the difference in the mass-absorption coefficients $(\mu_2/\rho - \mu_1/\rho)$ is .7 and in the other it is .4 approximately. The first case would correspond to one beam being in "α" state and the other in "γ" state; whereas the second case corresponds to the beams being in "α" and "β" states or "β" and "γ" states respectively.(See fig.29.) Thus, Barkla and Mackenzie's comparative study of two scattered beams gives substantially the same results as would be expected from the results of our experiments, where scattered radiations for various angles are compared with the primary radiation.

Theories of change of wavelength on Scattering in relation to our experiments:

The quantum theory of scattering proposed by Compton and Debye, and the sime-classical theory of scattering by Försterling and Halpern both demand a change in wavelength of a radiation on scattering. The change according to both theories is given by the relation.

$$\lambda_\theta - \lambda_0 = 2\Lambda \sin^2\frac{\theta}{2}$$

where $\Lambda = \frac{h}{mc} = 0.0242\text{Å}$

and θ = angle of scattering.

If a change in wavelength of a radiation is associated with a change in its absorbability in <u>all</u> substances, as has hitherto been assumed, none of our experiments in Case A show any sign of such a change for very soft rays. If there is any change, it must be less than one tenth of the difference demanded by the above formula. A general quantum theory proposed by Compton however, requires a certain limiting frequency for the primary radiation to show such a change in wavelength; the change should appear only when the energy is sufficient to eject electrons from the atom. On this theory, therefore, we should expect equality of penetrating powers of the primary and scattered radiation in the region of low frequencies. On the other hand, the frequency at which the difference should appear between the primary and secondary radiation, would depend on the material of the scattering substance. In our experiments however, the difference between the primary and secondary radiation only appears after the J-transformation which is subsequent to the fundamental process of scattering; the critical absorbability for this transformation being different for different materials with which the radiation is tested.

We shall consider in this section only the case B of our experiments - which is the only case giving results at all capable of explanation in terms of a change in wavelength on scattering. It will be shown below that even these experiments in Case B, are entirely at variance with the Compton-Debye formula for wavelength change.

The constancy of the ratio of ionisations (S/P) produced by the "unintercepted" secondary and primary beams, may be interpreted as due to a balance of two opposing variations, namely. an increased absorbability combined with **diminished** intensity of the secondary beam; but it is impossible according to the theory of a change of wavelength, to see how the "intercepted" ratio S'/P' could be constant over a wide range of frequencies.

Let λ_1 and λ_2 be the wavelengths of the primary and secondary radiations respectively; then according to the Compton-Debye formula

$$\lambda_2 = \lambda_1 + \delta$$

$$\text{and} \quad \delta = 2\Lambda \sin^2\frac{\theta}{2}$$

The coefficients of absorption of these radiations in aluminium is given, at any rate to a first approximation, by

$$\left(\frac{\mu}{\rho}\right)_1 = K\lambda_1^3 + \frac{\sigma}{\rho}$$

$$\text{and} \quad \left(\frac{\mu}{\rho}\right)_2 = K(\lambda_1 + \delta)^3 + \frac{\sigma}{\rho}$$

where K is a constant and $\frac{\sigma}{\rho}$ is the scattering coefficient for aluminium, which we shall suppose to be the same in both cases.

$$\text{Then} \quad \left(\frac{\mu}{\rho}\right)_2 - \left(\frac{\mu}{\rho}\right)_1 = 3K.\lambda^2.\delta$$

Now, the constancy of the ratio S'/P' when primary and secondary beams both passed through x cm. of aluminium, only means that $\left(\frac{\mu}{\rho}\right)_2 - \left(\frac{\mu}{\rho}\right)_1$ is constant; for, as has already been shown

$$S'/P' = e^{-(\mu_2 - \mu_1)x}$$

thus, if there is to be a change in wave-length, the amount of this

(1) Gregor Wenzel (Physik.Zeitschr. 26,1925.p.450) has shown that for hard X-rays (λ = .0204Å) ~~has shown that~~ this formula agrees with the results of experiments on the distribution of intensities for various angles of scattering much better than the formulae given by P,Debye (Phys.Zeitschr.24.161,1923) and Woo (Phys.Rev. 25,444,1925); we are therefore employing Compton's formula for our purpose.

change should vary approximately inversely as the square of wavelength in order to agree with the simple experimental fact viz. S'/P' = constant. Such a conclusion is incompatible with the Compton-Debye formula, according to which the change in wavelength is independent of wavelength; on such an hypothesis therefore $(\frac{\mu}{\rho})_2 - (\frac{\mu}{\rho})_1$ should be proportional (to a first approximation) to the square of the wavelength and our horizontal lines for S'/P' should be lines sloping down to the right. We shall illustrate this discrepancy graphically.

Compton's formula[1] for the intensity of scattered radiation is:-

$$\frac{I_\theta}{I_0} = \frac{C}{\left[1+\frac{\Lambda}{\lambda_0}(1-\cos\theta)\right]^5}\left\{\frac{1+\cos^2\theta}{2}+\frac{\Lambda}{\lambda_0}\left(1+\frac{\Lambda}{\lambda_0}\right)(1-\cos\theta)^2\right\}$$

where I_θ = Intensity of the radiation scattered at angle θ to a distance r.

I_0 = Intensity of the primary beam.

$\Lambda = \frac{h}{mc}$ = 0.0242 A

$C = \frac{e^4}{c^4 m^2 r^2}$

θ = angle of scattering.

Now, the ratio of ionisations produced by the "unintercepted" beams (S/P) may be written as $k.\frac{I_\theta}{I_0}\;\frac{i_\theta}{i_0}$, where I_θ and I_0 are the intensities of the secondary and primary radiations, i_θ and i_0 the ionising coeffieiencts of these radiations, and k is a constant depending on the apertures. To a first approximation, again the ionising coeffieients may be taken proportional to the cube of the wavelength; hence

$$S/P = K.\left(\frac{\lambda_\theta}{\lambda_0}\right)^3 \frac{I_\theta}{I_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

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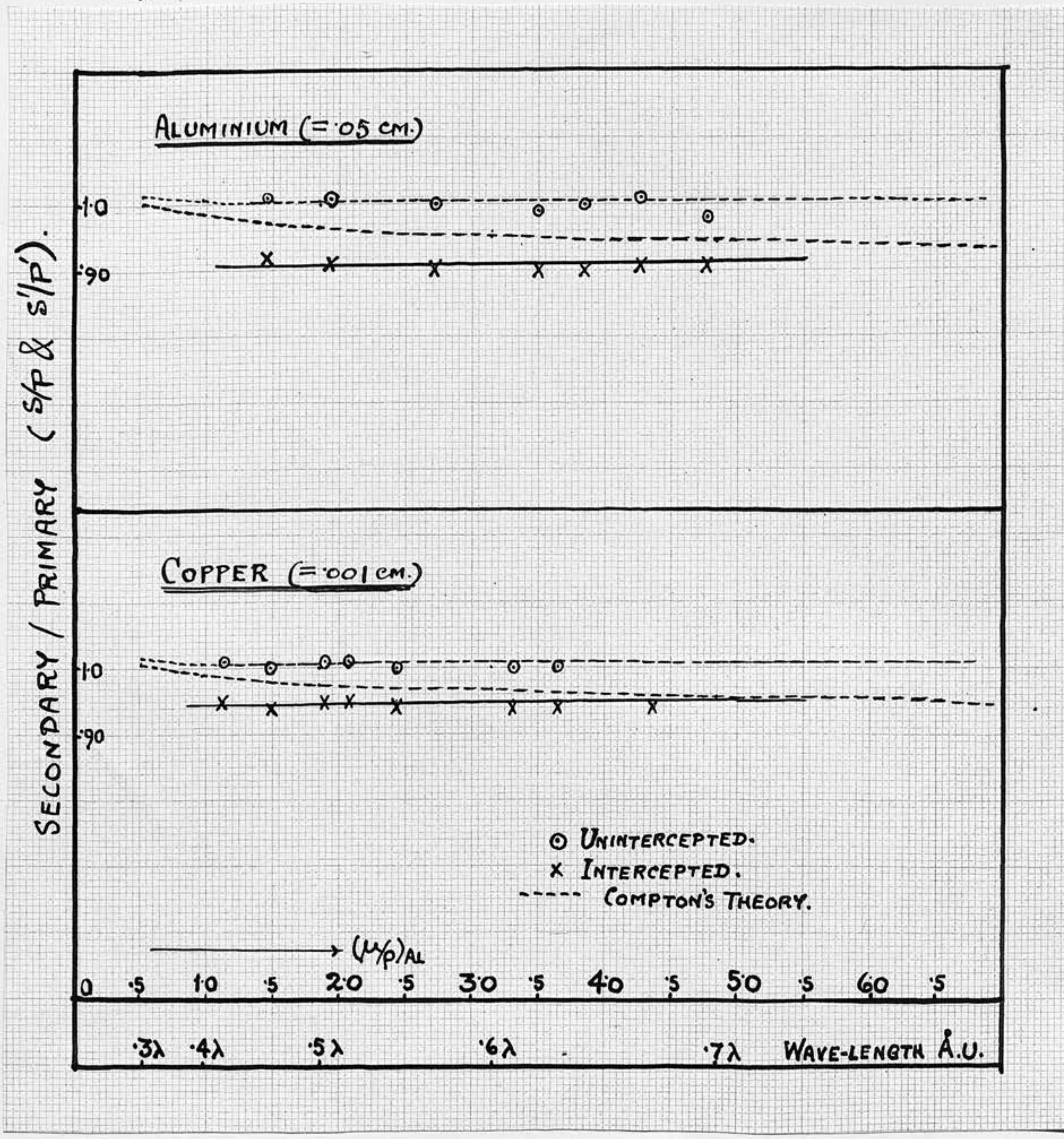

FIG. 30.

SEE TABLES XXVIII (a) & (b).

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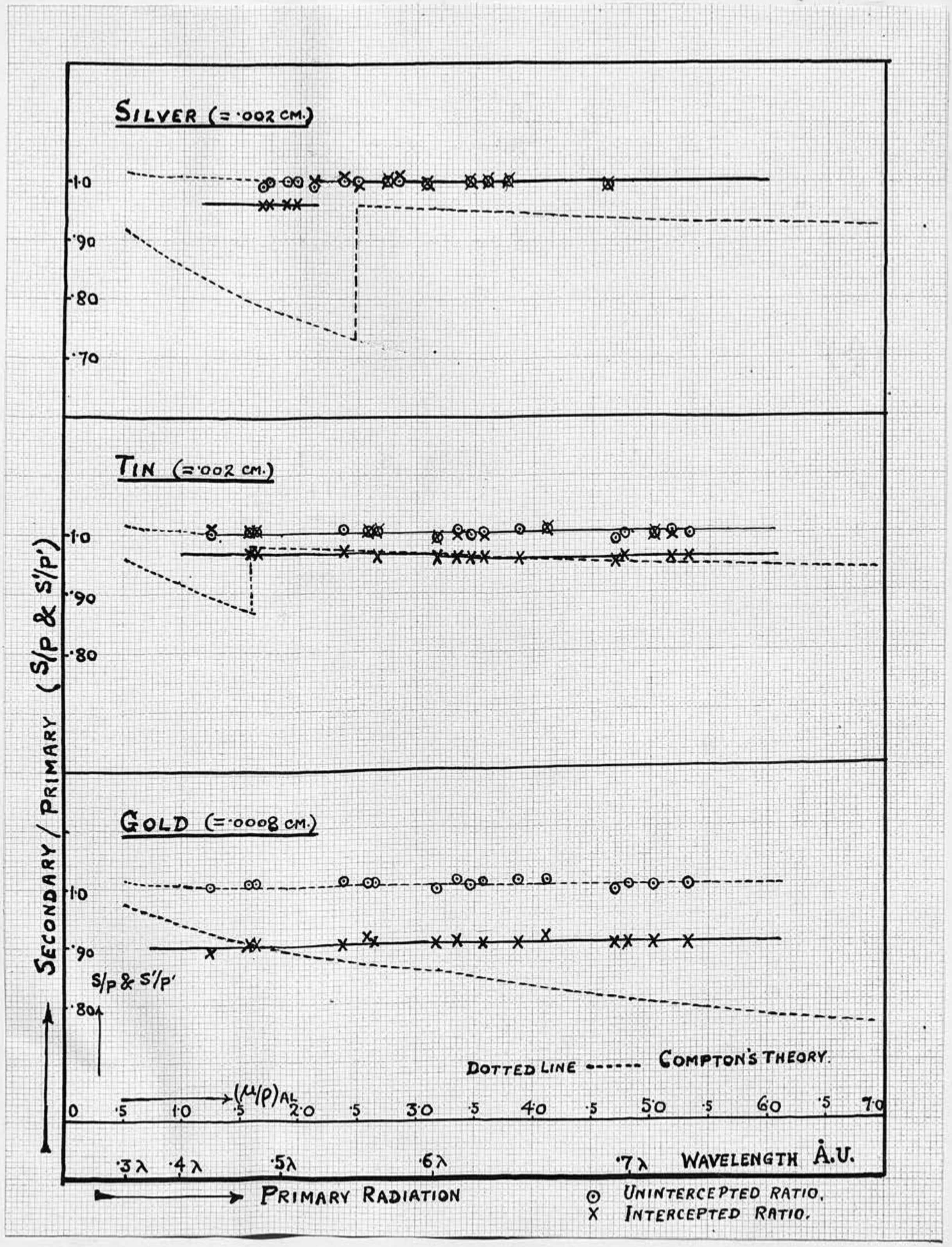

FIG. 31.

SEE TABLES XXVIII (c)(d)&(e)

In a similar way for the two beams intercepted by x cm. of an absorbing material

$$S'/P' = K.\left(\frac{\lambda_\theta}{\lambda_0}\right)^3 . \frac{I_\theta}{I_0} . e^{-(\mu_2-\mu_1)x} \quad \text{..................} \quad (2)$$

If we substitute in these two relations, the value of $\frac{I_\theta}{I_0}$ as required by Compton's theory, we can study the variation og S/P and S'/P' with the wavelength of the radiation and compare it with our experimental results.

$\left(\frac{\Lambda}{\lambda_0}\right)^2$ and higher powers can be neglected except for very short wavelengths and therefore when $\theta = 90^\circ$ we can write

$$\frac{S}{P} = \text{Constant} \;.\; \left(\frac{\lambda}{\lambda_0}\right)^3 . \frac{1}{1+3\frac{\Lambda}{\lambda_0}} \quad \ldots\text{).........} (1)\text{a}$$

and

$$\frac{S'}{P'} = \text{Constant} \;.\; \left(\frac{\lambda}{\lambda_0}\right)^3 . \frac{1}{1+3\frac{\Lambda}{\lambda_0}} . e^{-(\mu_2-\mu_1)x} \quad \text{.........} (2)\text{a}$$

In (2) $\cancel{\lambda}$a, $(\mu_2-\mu_1)$ is the difference between the absorbabilities of the secondary and primary radiations correspond-;ing to Compton's theoretical change in wavelength which is .0242Å when $\theta = 90^\circ$. This change in the absorbability is calculated from the relation $\frac{\mu}{\rho} = K\lambda^3 + \frac{\sigma}{\rho}$, obtained ~~by~~ from Hewlett,[1] Richtmyer & Warburton[2] & Richtmyer.[3] In tables XXVIII (a), (b), (c), (d) and (e) are give the computed values of S'/P' and S/P for various wavelengths, and the observed values obtained in our experiments.(Case B). There is not the slightest sign of agreement between our results and Compton's theory.(See fig. 30, and 31).

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(1) Hewlett. Phys. Rev. March 1921.
(2) Richtmyer & Warburton Phys.Rev. Dec.1923.
(3) Richtmyer Phys.Rev. Jan.1926.

In computing the values of $\left(\frac{\mu_2}{\rho}-\frac{\mu_1}{\rho}\right)$, corresponding to Compton's wavelength change of .0242A, the presence of the "modified" scattered X-radiation has alone been taken into consideration, although the spectra of scattered X-radiations reveal unmistakeably two distinct lines - the "modified" and the "unmodified". In a recent photometric study of spectrograms P,A,Ross[1] estimates the ratio of the intensities of the "unmodified" and "modified" lines in the case of Mo. K-radiation scattered by graphite at 90° to be .59. If we allow for this "unmodified" scattering, the average wavelength of the scattered radiation as a whole cannot be longer than that of the primary radiation by more than .015Å. For smaller angles of scattering, the change in the average wavelength will be still smaller; for, according to Ross the "unmodified" scattered radiation at 60° is more than double the "modified" radiation, and at 30° the "modified" is only a fifth of the "unmodified".

Our experimental results for various angles of scattering too, are not agreement with the Compton-Debye theory. The difference between the absorbabilities of the secondary and primary radiations should according to this theory, depend on the angle of scattering since the required change of wave-length is given by

$$\lambda_\theta - \lambda_0 = 2\Lambda \sin^2\frac{\theta}{2}$$

Our results on the other hand, show that this difference is quite independent of the scattering angle. This is shown

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(1) P,A.Ross, P,N,A.S., Sept, 1925.

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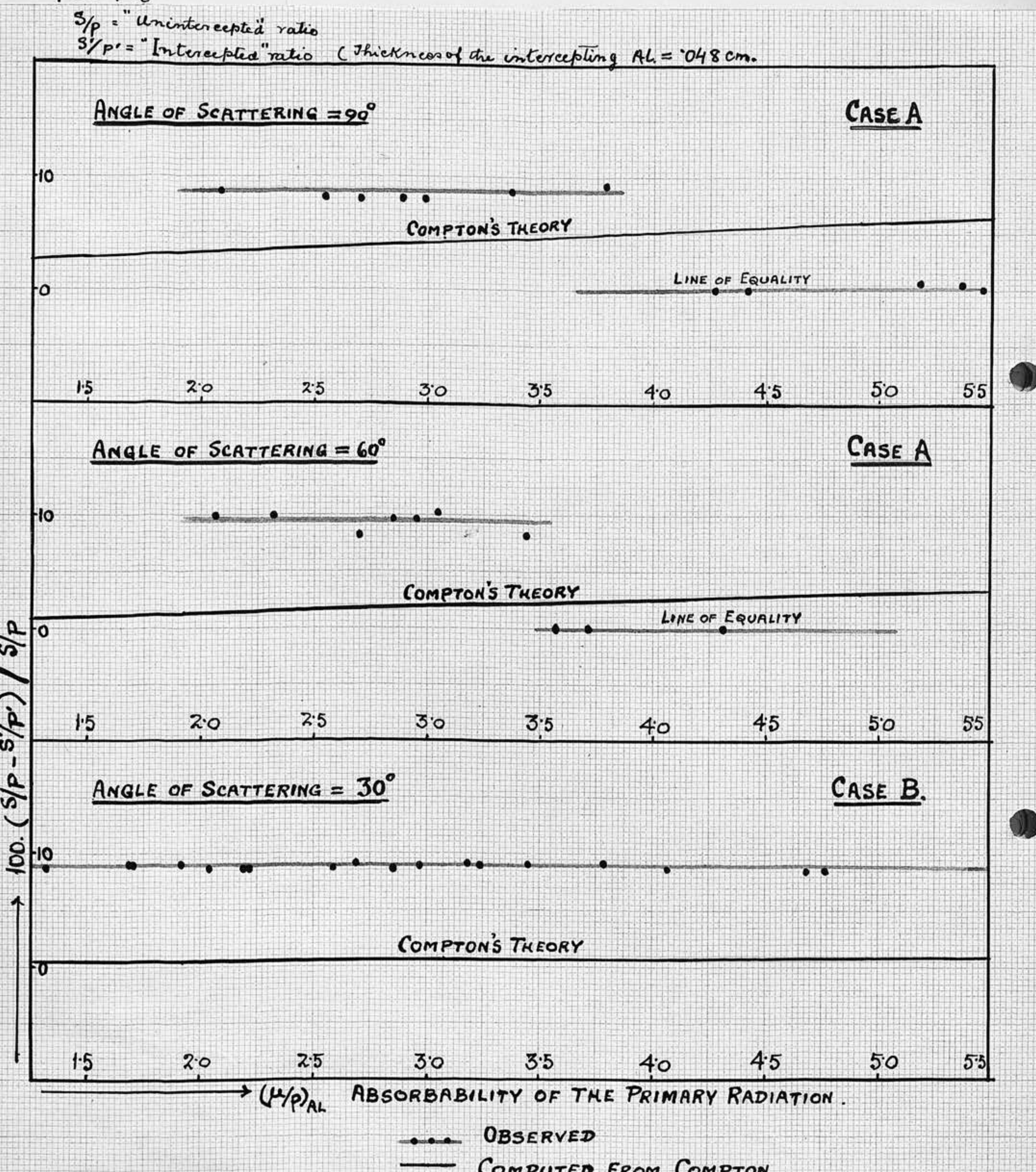

FIG. 32.

SEE TABLES XXIX (a) (b) & (c).

graphically in fig,32. (See tables XXIX (a),(b) and (c)).

The fractional fall in the ratio of the ionisations due to transmission of both secondary and primary through a thickness x of the absorbing substance, which is $\frac{S/P - S'/P'}{S/P}$ i.e. $1 - e^{-(\mu_2-\mu_1)x}$, is calculated from the Compton-Debyre formula for scattering angles 30°, 60° and 90°, amd is plotted against various wavelengths. Our results are entirely different from what is expected from Compton's theory.(1)

The nature of the J-transformation:

It has been shown that the J-transformation of an X-radiation is the change from one level of activity to another, the most remarkable feature being that the various levels of activity depend of the average penetrating power of the complex radiation taken as a whole, but not on the individual harmonic constituents of the complex radiation. It has also been shown with scattered X-radiation that a change of activity in one substance, from level to level, may take place without the least indication of any corresponding change in a second substance. The question now naturally arises as to the nature of this change of activity; what does this transformation really

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(1) Compton's absorption experiments for various angles of scattering are in good agreement with his theory. See Phil.Mag. Nov.1923. The work of F.Dessauer and R.Herz, also on the distribution of hardness of the rays scattered at various angles, using a photometric absorption method, agrees very well with Compton's theory, See Zeits.f.Physik.27, 1st half,Aug.28,1924. Our experiments however, lead to altogether different results.

involve? In answer, we must recall here that we have observed two distinct <u>alternative</u> cases of the J-transformation:

(1) At a particular value of the average penetrating power of a radiation, there is a very large absorption in a thin layer of the absorbing substance, during transmission, attended by a subsequent slight increase of absorbability in the substance in which the transformation has taken place.

Thus, if μ_1 = the "unmodified" absorption coefficient previous to the transformation and μ_2 = the "modified" absorption coefficient and x = the thickness of the intercepting substance, we have

$S' = S.e^{-\mu_1 x}$ previous to the J-transformation

and $S' = S.e^{-\mu_2 x}$ subsequent to the J-transformation.

$(\mu_2 - \mu_1)$ is constant for each substance between two discontinuities

(2) Alternatively, at a certain average penetrating power of a radiation there takes place a large absorption in a thin layer of the absorbing substance <u>without</u> any subsequent increase in the absorbability of the radiation; so that if the law of absorption before the J-transformation is given by

$$S' = S.e^{-\mu_1 x}$$

after the J-transformation it will be given by

$$S' = K.\ S.\ e^{-\mu_1 x}$$

These two alternative cases would correspond (1) to an absorption-edge and (2) to a line-absorption, if a photographic plate were exposed to a complex radiation immediately after transmission through a wedge of aluminium or any absorbing material.

At a certain thickness of the wedge, where the requisite hardness for the J-phenomenon is attained after the heterogeneous beam has been filtered through it, the photographic plate would show in the first case a sudden sharp edge and then a gradual fading effect; whereas in the second case the plate would simply show a white line on a dark background. The absorption-edge as well as the absorption-line[1] has been observed in the K, L and M series of radiations, but these are due to a resonance-effect produced by a particular constituent of the radiation, whereas in the case of the J-transformation, it is on the attainment of a particular average"absorption-coefficient" of the radiation that either and edge or a line of absorption is produced.

Barkla's[2] researches on the J-phenomenon led him to suggest at one time that the J-transformation involved an absorption of the radiation followed by a re-emission of radiation of somewhat greater wavelength proceeding in the original direction of probagation. It was thought that there was a certain average penetrating power of a radiation at which the absorbing substance would suddenly begin to emit radiation of a somewhat longer wavelength. According to this view however,

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(1) Observations of Lindh (see"The"Spectroscopy of X-rays" by Siegbahn, p,134,& p,145) Stenström & Fricke with light elements revealed absorption lines instead of edges under complicated conditions. That these are due to a resonance effect cannot however be said with certainty; on the other hand it is probable that they are examples of Barkla's J-phenomenon.
(2) Barkla, Nature Nov.17.1923.

an absorption edge - but no absorption line - is expected when the photographic plate, placed immediately at the back of a wedge, is exposed to a source of heterogeneous X-radiations. Although the existence of these absorption lines and numbrous other facts (which have been mentioned in several papers by Barkla and his associates) are strongly opposed to this suggestion - namely, the change of wavelength during transmission through matter - it has been still regarded by Barkla as an open question in view of the vast possibilities opened up by the discovery of a new X-ray phenomenon -the J-phenomenon. We shall give here a further experimental evidence against the idea of an increase in wavelength of a radiation during transmission. This evidence can be taken as deciding the point beyond any dispute - so long as we assume that the change in the wavelength of a radiation is always associated with the change in its mass-absorption-coefficient in <u>all</u> substances.

Two identical sheets of silver, or of tin, are placed, one in the path of the primary radiation and the other in the path of the secondary - immediately after transmission through filters of aluminium or paper of equal thickness. If the J-transformation (in scattered radiations) involves a change of wavelength <u>in the process of transmission</u>, we should expect that, subsequent to transmission through aluminium or paper, in which the J-phenomenon has already taken place, the secondary beam would be more absorbable than the primary, not only in aluminium or paper, but also in <u>all</u> substances. The ratios of ionisations produced by the "intercepted" secondary and primary radiations (S'/P') are determined with and without the two similar sheets of silver or tin, placed after

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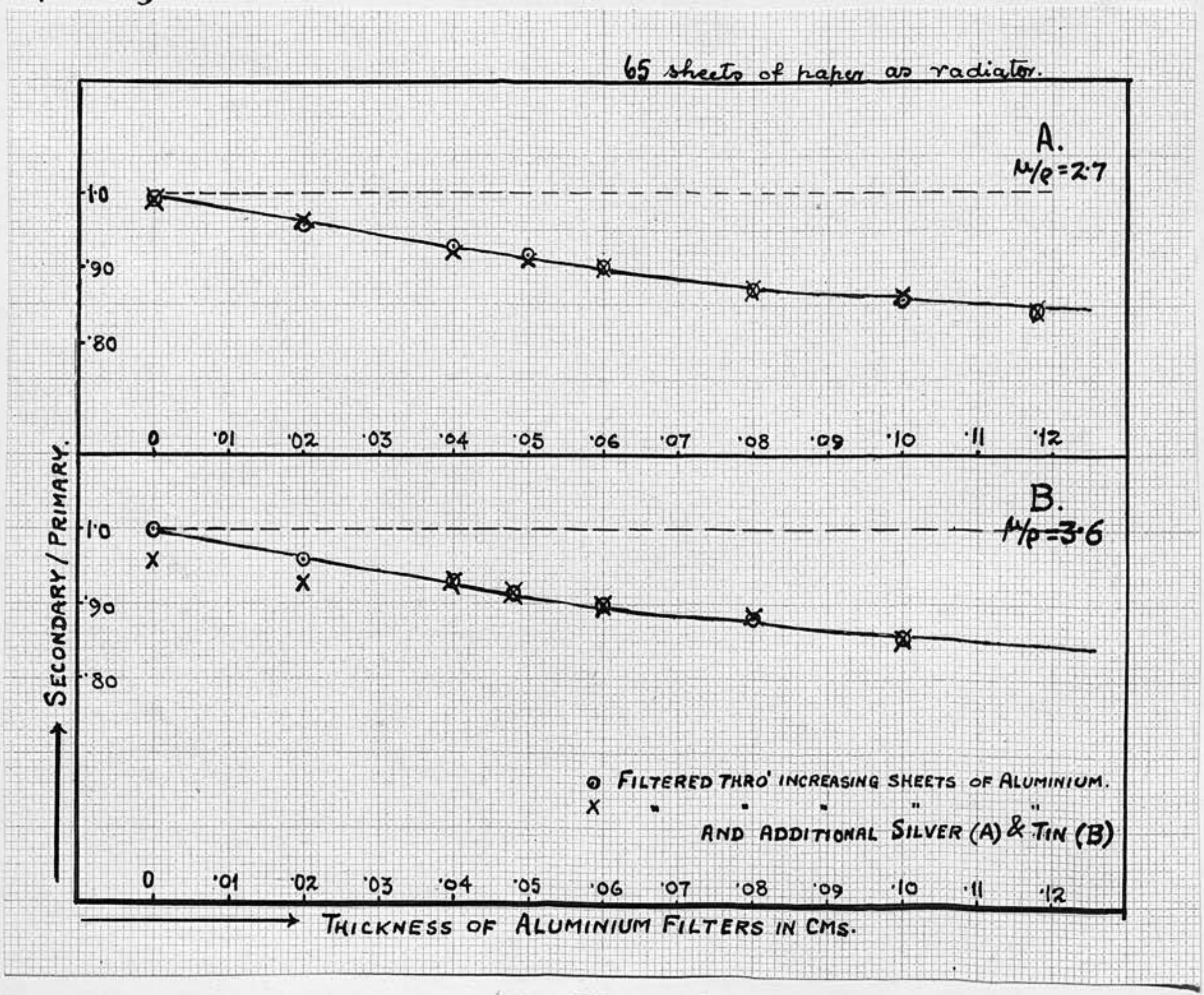

FIG. 33 (a).

SEE TABLE XXX

successively increasing equal thicknesses of aluminium or filter paper. The ratios(S'/P')however, are found to be identical in the two cases - even though the J-transformation of scattered radiation has already taken place in aluminium or paper, and the secondary beam has appeared more absorbable than the primary. This shows quite definitely that even after the J-transformation, has taken place in certain substances and the secondary beam appears to have become a "modified" radiation, if the absorbability is measured in those same substances, it may nevertheless have, after passing through those substances, precisely the same absorbability as the primary if measured in other substances, such as silver and tin; in other words, experiments have shown that the penetrating powers of secondary and primary radiations may appear equal when measured in some substances e.g.,silver and tin, even after the beams have passed through plates of materials which exhibit or produce a difference of penetrating power as measured in themselves.(1) These experiments are therefore, directly contradictory to any theory of a change in wavelength in the process of <u>either scattering or transmission</u>. The only possibility of reconciling the results of these experiments with the theory of a change in wavelength is to assume that there can be a change in the wavelength of a radiation without a corresponding change in its absorption.

Fig.33(a) shows the difference in Aluminium from the very beginning between the primary and secondary radiations, the ratio S'/P' gradually diminishing with the increasing thickness of the

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(1) Barkla & Khastgir, Nature, Feb.13,1926.

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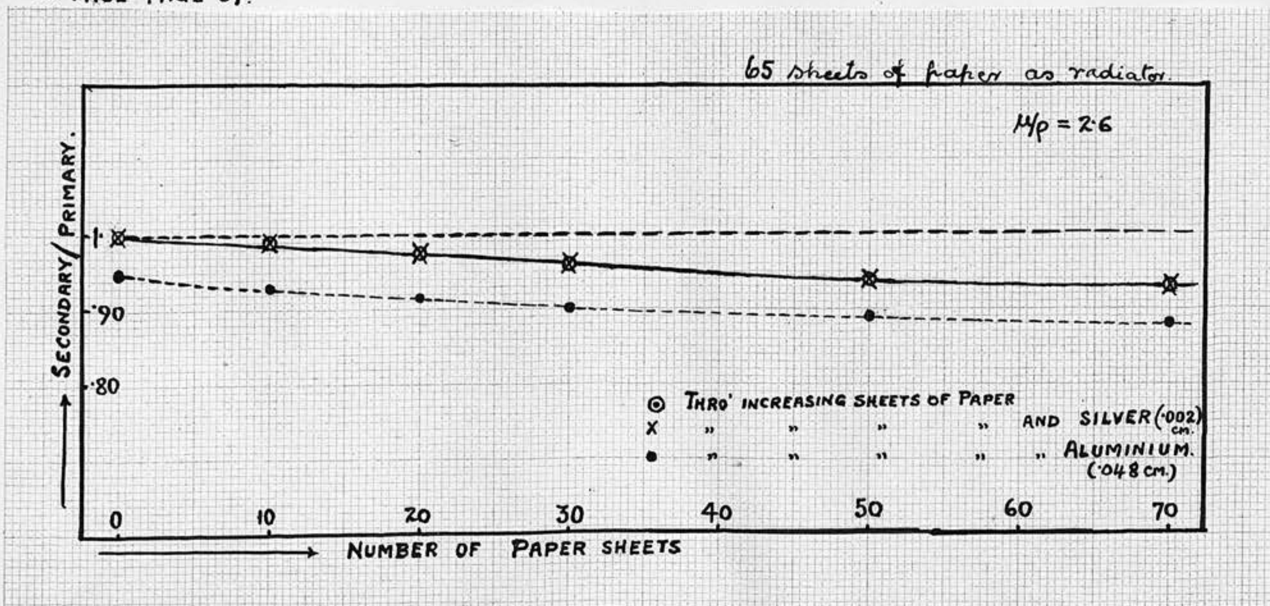

FIG. 33(b)

SEE TABLE XXXI

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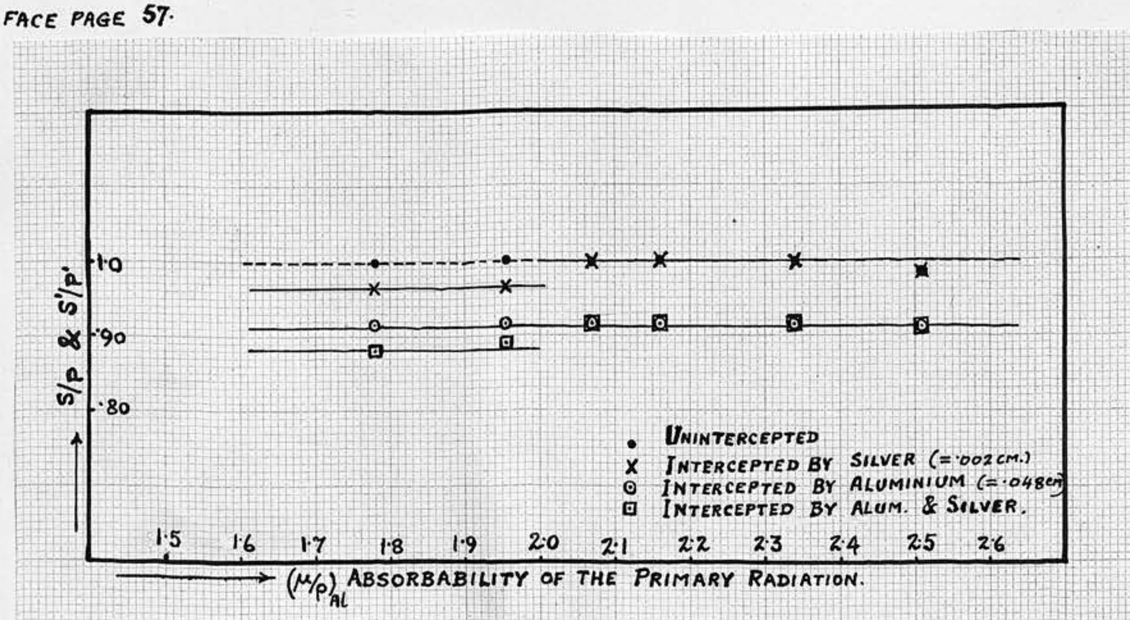

FIG. 34

SEE TABLE XXXII

aluminium filters; it also shows that there is no further difference in the ratio, when the primary and secondary radiations passed through silver or tin subsequent to transmission through the aluminium sheets. (See table XXX). Similar results are also obtained when radiations are filtered in the same way through increasing thicknesses of filter paper. Here too, there is no further change in the ratio, when the silver or tin sheets of equal thickness are placed after the paper filters in the paths of the secondary and primary beams. See fig.33(b) and table XXXI.

The same feature is also demonstrated in fig.34 (See table XXXII). This figure definitely shows that over a range of wavelengths, the intercepted ratio S'/P' remains unchanged even after the beams have passed through equal thicknesses of silver subsequent to their transmission through aluminium,. The difference in the ratio appears only when the J-transformation takes place in silver at the critical absorbability for this metal. (Silver and tin are the most suitable substances for a demonstration of this feature, since the critical absorbabilities for silver and tin differ very widely from those of aluminium or of paper; thus, there is a fairly wide range over which the J-transform:ation can be shown to have taken place in aluminium or paper, but not in silver or tin, even after transmission through aluminium or paper.)

What then is the J-phenomenon? To answer this, we must come to a world of entirely new conceptions; for, as a logical consequence of simple experimental facts we are compelled to make a very broad and bold generalisation that there must be a complete divorce of the activity of an X-radiation from the frequency of that radiation. Scores of experiments have demonstrated that there are various alternative absorptions for what are, to all appearances, radiations of the same wavelength. Barkla has further shown that corresponding to these alternative absorptions, there are alternative corpuscular emissions and alternative ionisations in the substances exposed to X-rays. Thus, it can be said that a change in the activity of an X-radiation can take place without a corresponding change in the wavelength; This change of activity is what we have called the J-transformation - the transition from one level of activity to another appearing in the form of discontinuities.

It has been emphasised already that the critical condition which governs the change of activity is the average "absorption - coefficient" of a complex radiation and not an individual harmonic constituent of the radiation. It appears therefore, as Barkla(1) has suggested, that the J-phenomenon can be more clearly described as one dependent on something analogous to the "temperature" of the whole beam of X-radiation; for the term "temperature" also means an average and likewise, the properties of a substance at a given temperature is dependent only on the <u>average</u> energy and <u>not</u> on the energies of the individual molecules.

This analogy can be pressed further. It is well known that when a vapoür or a solution is supersaturated, there takes place suddenly what would, under normal conditions, have been a more

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(1) Barkla and Mackenzie, Nature Jun.20, 1925.

gradual change of state. In these cases, the discontinuity appears in the form of a sudden condensation or evaporation or a sudden precipitation of matter. Correspondingly, it appears that, when an X-radiation is transmitted through matter, absorption does not take place at the rate which obtains under slightly different conditions. The discontinuity in this case takes the form of a precipitation of absorption. Cases A and B of the filtering experiments, where the primary and secondary radiations are filtered by gradually increasing thicknesses of an absorbing substance, bring out the analogy very clearly. We might say that case B corresponds to the normal state of affairs, while in case A the difference in the secondary and primary radiations is, in some way or other, held up, up to a particular thickness of the absorbing material, when the last layer suddenly precipitates the change; the magnitude of the change is just such as to compensate for what might, under different conditions, have taken place in the earlier layers of the absorbing substance. It looks as though the last layer produces in some way the necessary conditions for certain electrons to act as nuclei for a sudden "evaporation" (or condensation) of the energy from the radiation - an "evaporation" which might, under other conditions, have taken place gradually from the earlier layers. The necessary condition, as we have seen, is provided when the average absorption-coefficient of the heterogeneous radiation reaches a certain critical value within the absorbing substance traversed; or, in other words, when the complex radiation attains a particular "temperature".

It is not possible as yet to see how far this analogy will take us, but the sudden disappearance of energy from the beam of X-rays and the simultaneous appearance of energy in electrons of the transmitting substance most certainly indicates a concentration of the energy of the beam in certain atoms of the substance traversed; and whatever radiation may be - a wave or a quantum or both - it appears that there is a change of state of the radiation in this sense. Like the melting, freezing or boiling point, which marks the transition of a substance from one state to another, the particular value of the absorbability denotes the end of one and the beginning of another state of the radiation. In this sense the J-transformation of X-rays which merely means a transition from one state to another, takes place when the "temperature" T_1 is greater than T_2, where T_1 is the average penetrating power ("temperature") of the beam and T_2 is the penetrating power characteristic of the substance traversed.(1)

From this point of view, it is also to be expected that, the critical absorbability for a particular substance, or using the thermal nomenclature, the characteristic "temperature" should depend on the atomic and even on the electronic structure of the absorbing substance in some such way as the melting, freezing or boiling point depends on the material as well as on the surrounding atmosphere. Thus, although in a general way

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(1) It is just possible that Stoke's law of fluorescence may need to be restated in a similar way, in order to make the law more general and to express what is most fundamental. At present this is nothing more than a speculation.

we can say that the value for the critical absorbability for the J-transformation decreases with the atomic number, it should be borne in mind that there is a great possibility that the electronic distribution inside the atom will influence the J-transformation, especially with heavier elements of complicated electronic structure. This might explain why the J_2-discontinuity for copper appears at a smaller penetrating power of the radiation than in aluminium. It is also quite feasible that within the range of J_1, J_2, and J_3-discontinuities in aluminium, we have obtained in silver four discontinuities, the last two appearing very close together as a sort of doublet.

The J-phenomenon in Gases:

A change in the level of X-ray absorption in a substance in the solid state, has been shown to take place at a particular "temperature" of the radiation, characteristic of the material; but such a change does not seem to occur in a substance in the gaseous condition, e,g,. air; for, although in our experiments the primary and secondary beams have to pass through some distances of air, the ratio of ionisations produced by the "unintercepted" secondary and primary beams is found to be perfectly continuous over a wide range of wavelengths.

The negative effect in air in our experiments means either that the J-absorption has taken place in both the primary and secondary radiations, or that such an effect does not or is not likely to take place in a gas. A systematic study of the J-absorption in gases, however, has not been made; but it does not seem improbable that the compactness of electrones in an atom, in the solid state, or the looseness of the electrones in gaseous state, should make a difference in the behavious of a radiation according to the state of the matter traversed.

It is for the same reason probably that the J-ionisation is not frequently observed. According to all accepted ideas, the absorption of the radiation by a substance in the solid state is always associated with the ionisations produced in it when in the gaseous condition; thus, if there is a sudden change in the X-ray absorption in a substance, it is expected that a corresponding change in the ionisation should also be observed. In fact such a change in the ionisation produced in a gas was, under certain unknown conditions, observed by Barkla and White[1], and Barkla[2] in the region of the J_2-discontinuity. The same was also observed by C.T.R.Wilson[3] in his cloud experiments; but it surprising that in the hundreds of experiments where the J-absorption-discontinuities in various substances have been noticed, there was found no indication of any J-ionisation discontinuity in the gas that was used in the ionisation chambers. This negative result again, indicates <u>either</u> an entire absence of the J-ionisation effect <u>or</u> the

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(1) Barkla & White, Phil.Mag.(in the Press) 1926.
(2) Barkla, Phil.Trans,1917.
(3) C,T.R.Wilson, Proc.Roy.Soc.Lon.CIV.Section A.1923.

The photographic plates in Wilson's cloud experiments revealed a new class of tracks of ions called by him "the fish tracks". These "fish tracks" were not seen in the plates when the wavelength of the incident radiation used exceeded .5Å. The maximum wavelength of the radiation consistent with the production of these "fish tracks" is between 0,4 to 0.6Å according to Wilson's estimate. Bothe's photographs (Zeits.f.physik. 16&20 1923) and those of Compton and Simon (Phys.Rev. March 1925) reveal these "fish tracks" also. Their number varies continuously with the wavelength of the radiation. These might be considered as the Case B of our experiments.

simultaneous occurrence of the same in both the chambers. If the latter alternative is true, we do not see why the J-ionisation should be produced by both primary and secondary radiations, when the J-absorption is only shown by the secondary. No definite conclusion can however, be reached unless more experiments are made and more facts are known. We shall give here the results of one of two series of observations where there was observed a sudden increase in the ratio of the ionisations produced in SO_2 by the "unintercepted" secondary and primary radiations at a particular value of the absorbability of the primary radiations. It was in the region of J_1-discontinuity viz. $(\mu/\rho)_{Al} = 4.0$ nearly, that the "unintercepted" ratio S/P suddenly rose, whereas the "intercepted" ratio S'/P' using aluminium in the paths of the primary and secondary radiations, dropped very suddenly at the usual position for the J_1-discontinuity in aluminium and by the usual amount.(1) The fact that the atomic of sulphur is one less than that of aluminium lends support to our conclusion that the rise is due to J-ionisation in SO_2 and is likely to appear at a slightly higher absorbability than the J-absorption in Aluminium. It is here assumed however, that when the beams are intercepted, the J-effect takes place in the intercepting aluminium and not in the ionisation chamber: whereas when there is nothing to intercept the beams and they come straight

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(1) It cannot however be said with exact precision whether the rise in ionisation in SO_2 occurred earlier (i,e, at lower frequency) than the increase in absorption by aluminium; for the two critical points were very close together.

KHASTGIR.

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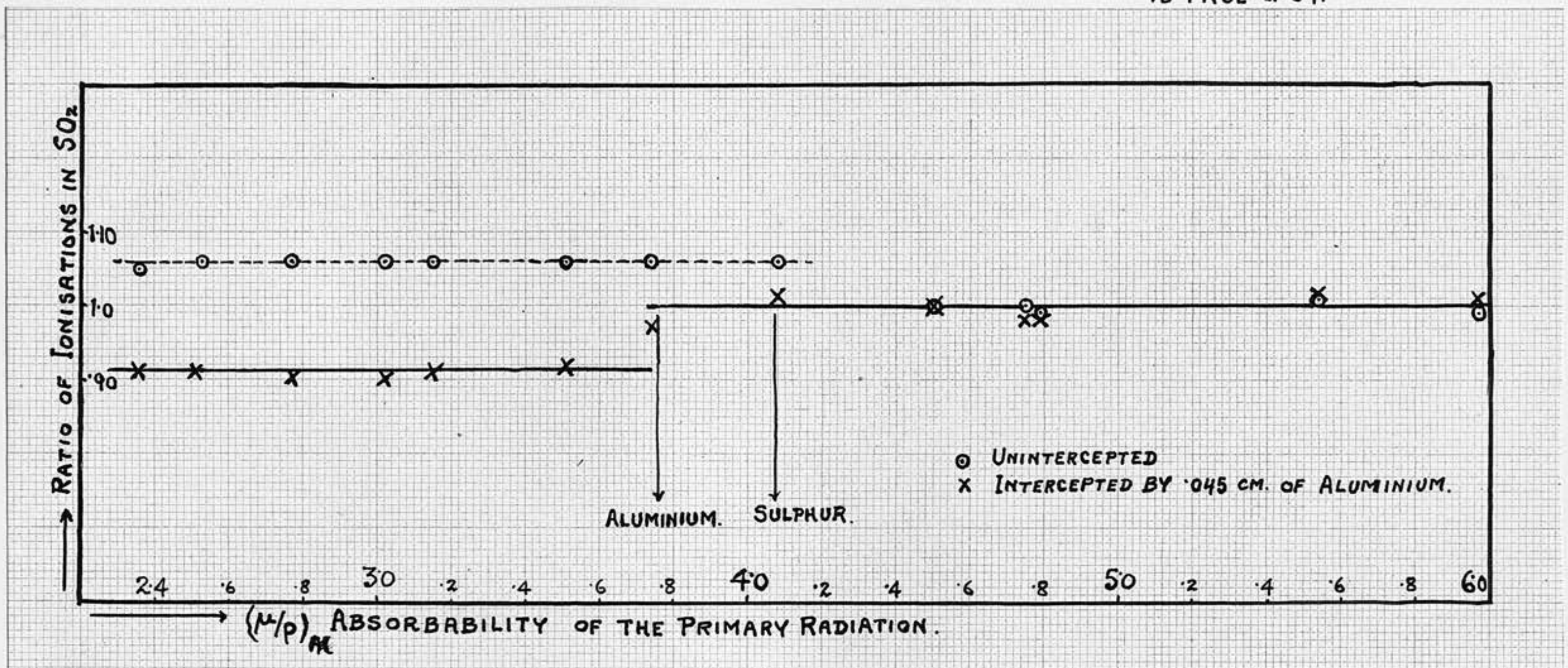

FIG. 35.

SEE TABLE XXXIII

to the chambers, the J-effect occurs in the gas in the ionisation chamber. In table XXXIII. is given the actual experimental values for the "unintercepted" ratio S/P and the corresponding "intercepted" ratio S'/P' for various absorbabilities of the primary radiation. This is illustrated in fig. 35. In these two series of observations the scattering substance consisted of twenty-five sheets of filter paper and the source of X-rays was a "Leviathan" tube with a tungsten anticathode. Scores of other series of observations using the very same radiator and the very same source of X-rays did not show this sudden rise.

It should be recalled here that in Case B there were a few series of observations in which the difference between the primary and secondary radiations, even for soft rays, was found to be what would be expected after the J_2-discontinuity; i.e. beginning from a very soft radiation and gradually hardening it, it was found in a few series of observations that from the very beginning the level of the "intercepted" ratio S'/P' was what would be anticipated after the J_2-discontinuity in aluminium. This has been taken to indicate that under certain conditions the J_2-level of absorption is possible even before the critical absorbability for it is attained; but in view of the sudden rise in SO_2 as observed in these two cases, it is also likely that J-ionisation in SO_2 combined with the J_1-absorption in aluminium is responsible for this double drop in the "intercepted" ratio S'/P'. It is therefore left still as an open question.

The Critical Conditions:

Attempts to discover the critical factors which control the J-phenomenon and to find out the difference between the conditions of experiments in Case A and those in Case B have so far been unsuccessful. Sometimes the J-discontinuity occurred day after day, while at other times it vanished altogether under apparently identical conditions. More remarkably still, at certain times, it was found that some unknown controlling factor varied during a series of observations so that the discontinuity appeared and disappeared before our eyes although we could not detect any difference in the conditions.

Experiments were made with many possible variations; viz. with strong and with very feeble radiations, with narrow pencils and wide beams, with heterogeneous and approximately homogeneous radiations. Different X-ray tubes with different anticathodes were tried. Different methods of exciting the X-rays and different arrangements of apparatus were also employed. There was however no evidence of dependence on any of these. To see whether the conditions controlling the phenomenon are related to any possible "fatigue-effect" in the absorbing substance, the absorbing sheets which had long been exposed to X-rays were replaced by fresh and previously unexposed sheets; but no such "fatigue-effect" was observed.

Although the critical factors do not seem to depend essentially on any of these things, the following which appeared to be sometimes favourable to the J-transformation should be noted:

(1) The heterogeneity of the radiation: It has appeared that at least in some experiments with tin or silver as an absorbing

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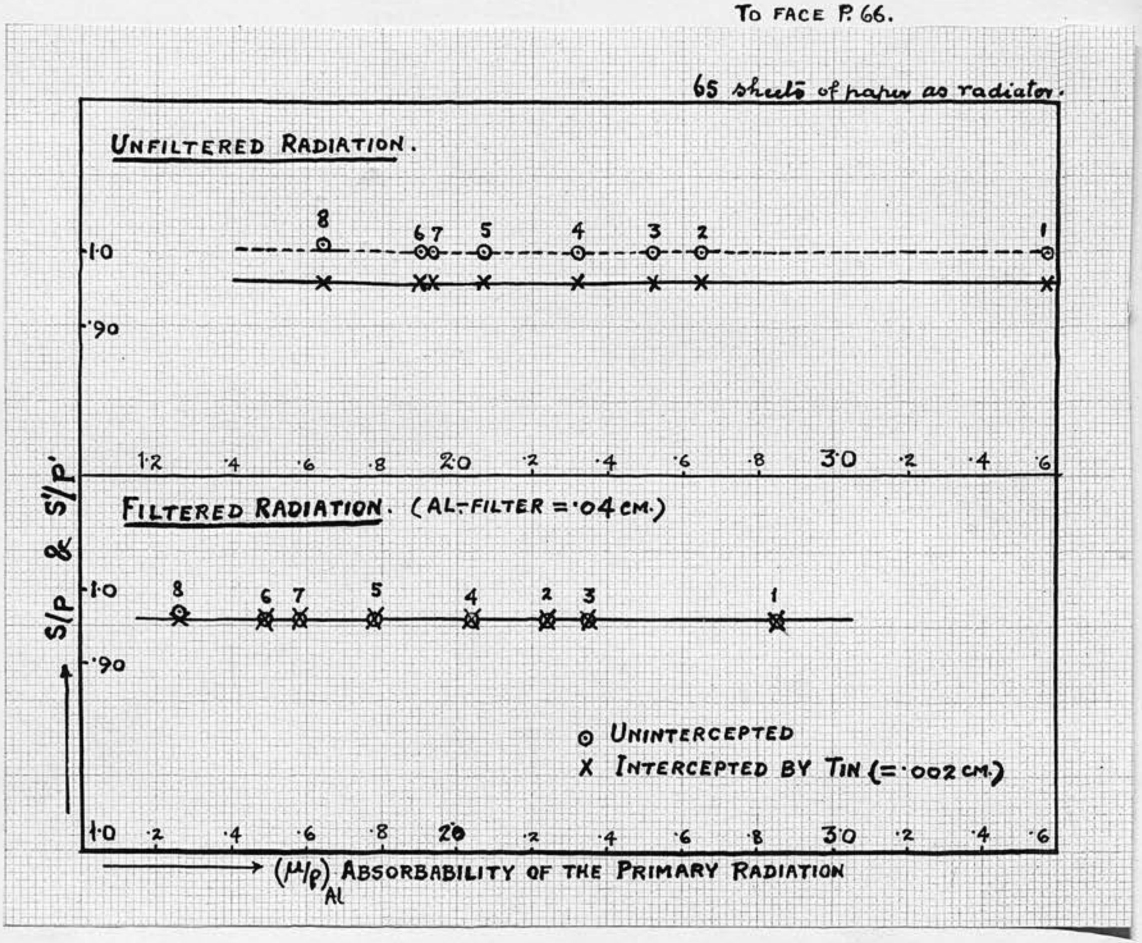

FIG. 36.

SEE TABLE XXXIV

substance, a heterogeneous beam of X-radiation is favourable to the J-phenomenon. We shall give here experimental results which show how the behaviour of a heterogeneous radiation in tin is sometimes different from that of a comparatively homogeneous radiation. Using a very heterogeneous radiation the ratio of the ionisations produced by the secondary and primary radiations (1) when they are unintercepted and (2) when they are intercepted by the same thickness of tin, were determined, as usual, for various penetrating powers of the radiation. Similar ratios were also determined using a comparatively homogeneous radiation, obtained by passing the heterogeneous primary beam through a thick filter of aluminium. In order to avoid any possible effect due to a change in the primary radiation, the readings with "unfiltered" and "filtered" radiations were taken in alternative pairs so that corresponding points were obtained with practically identical states of the X-ray tube. In the case of the "unfiltered" radiation, there was a difference between S/P and S'/P' over a range ($\mu/\rho_{Al} = 3.6$ to $\mu/\rho_{Al} = 1.4$) indicating that a J_1-transformation has already taken place in the secondary radiation, whereas in the case of the "filtered" radiation the ratios were identical over the same range, although there was a drop in the ratio S'/P' when $(\mu/\rho)_{Al} = 1.2$ - the value for the J_2-discontinuity for tin, This is illustrated in fig,36.. (See table XXXIV.) it should be noted that at other times when similar experiments with tin were performed using "unfiltered" radiations, the ratios were found either to be exactly equal or distinctly different over a long range of wavelengths. (See fig.17)

(2) The intensity of the radiation: It has been found that the J-phenomenon is observed more frequently with a scattered radiation which is comparatively feeble than with the primary radiation. In fact the demonstration of the J-absorption-discontinuities in this investigation, has been made possible because of the scattered radiation being more susceptible to the J-transformation than the primary. This has lent support to the view that probably the intensity of a radiation plays a part in the J-phenomenon. The observation of Barkla and Sale[1] (which have since been fully confirmed) that the equality in penetrating power between the primary and secondary radiations is obtained more frequently with a thin radiator than with a thick, also supports this view; for when we use a thin radiator, the radiation that is scattered is comparatively feeble and probably does not produce the J-phenomenon in the testing material to show the difference between the secondary and primary radia:tions, whereas the intense beam scattered from a thick radiator does. It should be noted again that the results which are shown in fig.36, as an effect of heterogeneity, might equally well be due to the feebleness of the radiation when it is filtered.

(3) The polarisation of the radiation: It is also just possible that the polarised state of the beam is favourable to the J-phenomenon; in this case however, we can see that the J-discontinuity should occur more frequently with scattered X-radiations than with primary or characteristic radiations.

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(1) BARKLA & SALE, UNPUBLISHED WORK.

Conclusions,

One of the most important conclusions from a study of the J-transformation of scattered X-radiations - is that there must be a complete detachment of the activity of an X-radiation from the wavelength of the radiation; or in other words there must be a separation of the quantum relationships from the frequency of a radiation. Thus it can be said, that under certain conditions at any rate, a change in the activity (corpuscular emission, ionisation and absorption) of a radiation can take place without any change of wavelength. It has been seen that such a change in activity takes place more frequently with the scattered X-radiation than with the primary, so that any difference that is observed between the secondary and primary radiations when measured by the activities of these two radiations in a particular substance is merely an instance of such a change in the activity of the scattered X-radiation and is not due to a difference in wavelength.

The question now arises of how to reconcile our experimental results with the spectrometer work on scattered X-radiation. Can there be a change in wavelength without any corresponding change in activity? Having shown the detachment of X-ray phenomenon from mere frequency, it seems just possible that diffraction methods indicate a change of wavelength, whereas our methods indicate no corresponding change of properties since we have seen that these properties are not fundamentally connected with waves.

It should not be overlooked however, that a change in the diffraction angle in the spectroscopic observations <u>might not</u> correspond to a change in wavelength; for, as has already been pointed out in the Introduction, a measurement of wavelength is dependent on the adequacy of the classical theory of diffraction and assumes the absence of any unforseen phenomenon. In view of the experiments on the J-phenomenon which have shown that the activity resulting in corpuscular emission, ionisation, absorption etc. does not vary continuously with wavelength, it is quite likely that anomalies will as a consequence appear in the spectrometer work. Appreciable refraction may also occur in a crystal when the absorption suddenly changes at a J-discontinuity.

With regard to Compton's "modified" scattered X-radiations we must therefore, accept one of the following possible alternatives:

(1) Wavelength may change without a corresponding change in the activity of an X-radiation. This appears possible only on the assumption of the dual nature of radiation in some such way as is suggested by Sir J.J. Thomson or

(2) The "modified" spectral line in the experiment of Compton and others, does not represent another wavelength in the secondary radiation incident on the crystal of the spectrometer, or

(3) The conditions essential to the production of the "modified" scattered X-radiation have not been realised in the hundreds of experiments wehave made on the phenomenon. This is highly improbable both from the variety of our experiments and from the fact that we do obtain under certain conditions what

superficially appears to be a change of wavelength.

The alternative possibilities are therefore, reduced to (1) and (2).

In conclusion I have great pleasure in expressing my indebtedness to Prof. C.G.Barkla D.Sc., F.R.S., Nobel-Laureate, for his invaluable assistance and stimulating interest during the progress of this work. My thanks are also due to the Council of the Scientific and Industrial Research for a grant which has made this research possible.

1st May. 1926

Physical Laboratory
University of Edinburgh

S.R. Khastgir.

FOR TABLES SEE APPENDIX.

APPENDIX.

31 TABLES.

Table I.

S/P = "Unintercepted" ratio S'/P' = "Intercepted" ratio.

	$(\mu/\rho)_{Al}$ Primary	S/P	S'/P' (Arbitrary units)
J_1-discontinuity	3.01	1.005 × x	.89 × x
$(\mu/\rho)_{Al}$ = 3.8	4.28	.99 "	.97 " .89 "
	4.83	1.00 "	.99 "
Thickness of the intercepting aluminium = .045cm.	3.82	.995 "	.89 " 1.00 "
	4.08	1.00 "	.99 "
	4.35	.99 "	.86 "
	3.17	1.00 "	.89 "
	2.97	1.00 "	.89 "
	3.75	1.00 "	.89 "
J_2-discontinuity	1.79	1.00 × x	.84 × x
$(\mu/\rho)_{Al}$ = 1.9	1.75	.995 "	.835 "
	1.52	.995 "	.83 "
	2.32	1.00 "	.92 "
	2.77	1.02 "	.925 "
Thickness of the intercepting aluminium = .045cm.	2.17	1.02 "	.92 "
	2.28	1.00 "	.92 "
	1.92	1.00 "	.84 "
J_3-discontinuity.			
$(\mu/\rho)_{Al}$ = .70	1.14	1.08? × x (not plotted)	.83 × x
	.68	.99 × x	.75 "
	.84	1.01 "	.825 "
	.86	1.01 "	.825 "
	.82	1.08? " (not plotted)	.83 "
Thickness of the untercepting aluminium = .108cm.	.67	1.01 × x	.76 "
	.75	1.0 "	.765 "
	.89	1.10? " (not plotted) 1.01 × x	.83 "
	.73	.99 " x	.765 "
	.66	.975 "	.76 "

See fig. 3.

Table II

J_1-discontinuity

$(\mu/\rho)_{Al}$ primary	S/P	$(S'/P')_{Al}$ x = .045cm.	$(S'/P')_{Cu}$ x = .001cm.
3.01	1.005 × x	.89 × x	- × x
4.28	.99 "	.97 " .89 "	.91 "
4.83	1.00 "	.99 "	1.00 "
3.82	.995 "	.89 " 1.00	.99 "
4.08	1.00 "	.99 "	1.01 "
4.35	.99 "	.86 "	.99 "
3.17	1.00 "	.89 "	.925 "
2.97	1.00 "	.89 "	.925 "
3.75	1.00 "	.89 "	1.00 "

J_2-discontinuity:

$(\mu/\rho)_{Al}$ primary	S/P	$(S'/P')_{Al}$ x = .045cm.	$(S'/P')_{Cu}$ x = .001cm.
3.25	1.01 × x	.905 × x	.94 × x
3.13	1.02 "	.91 "	.93 "
2.47	1.01 "	.91 "	.94 "
4.04	1.01 "	.91 "	1.02 "
2.95	1.01 "	.91 "	.93 "
2.37	1.00 " .98 "	.91 "	.88 "
2.09	.98 "	.905 " .88 "	.88 "
1.83	.96 "	.82 "	.88 "
1.70	.96 "	.82 "	.88 "
1.54	.96 "	.82 "	.88 "
1.43	.96 "	.82 "	.88 "

See figs. 4 & 5.

Table III

J_2-discontinuity:

$(\mu/\rho)_{AL}$ Primary	S/P	(S'/P')Paper = 130 sheets	(S'/P')$_{AL}$ x = .063 cm.
2.07	1.03 x x	.95 x x	.92 x x
2.0	1.03 "	.95 "	.92 "
1.91	1.03 "	.95 "	.90 "
1.79	1.02 "	.90 "	.90 "
1.77	1.00 "	.90 "	.83 "
1.58	1.00 "	.89 "	.83 "
2.28	1.035 "	.95 "	.915 "
2.08	1.03 "	.96 "	.92 "
2.06	1.02 "	.955 "	.92 "
2.23	1.02 "	.96 "	.91 "
1.86	1.02 "	.905 " .95 "	.90 "
1.85	1.01 "	.90 "	.895 "
1.70	.97 "	.90 "	.835 "
~~1.70~~	~~.97~~ ~~"~~	~~.90~~ ~~"~~	~~.835 "~~

See fig. 6.

Table IV

J_1 - discontinuity:

$(\mu/\rho)_{Al}$ Primary	S/P	$(S'/P')_{Ag}$ Thickness of Ag = .002 cm.
1.68	.99 x x	.96 x x
1.73	1.0 "	.96 "
1.88	1.0 "	.96 "
1.96	1.0 "	.96 "
2.01	1.0 "	.96 "
2.12	.99 "	1.0 "
2.38	1.0 "	1.005 "
2.5	1.0 "	.99 "
2.75	1.0 "	1.0 "
~~2.85~~	~~1.0~~ ~~"~~	~~1.0~~ ~~"~~
2.85	1.0 "	1.01 "
3.09	.995 "	.995 "
3.45	1.0 "	.995 "
3.55	1.0 "	.995 "
3.77	1.0 "	1.0, "
4.61	.995 "	.995 "

Table V

J_2-discontinuity: Thickness of Aluminium filter in the leadbox = .037 cm.

$(\mu/\rho)_{Al}$ Primary	S/P	$(S'/P')_{Sn}$ Thickness of Sn = .002 cm.
.946	- x x	.905 x x
.979	.99 "	.90 "
.989	.98 "	.90 "
1.03	.99 "	.90 "
1.14	.99 "	.90 "
1.20	.99 "	.94* " .90 "
1.21	.98 "	.99 " .90 "
1.26	1.015 "	1.0* " .94* "
1.30	1.005 "	1.005 "
1.37	1.0 "	1.0 "
1.49	1.0 "	1.0 "
1.58	1.0 "	1.0 "
1.78	1.0 "	1.0 "
2.04	1.0 "	1.0 "
2.24	1.0 "	1.0 "
2.35	1.015 "	1.0 "
2.85	1.0 "	1.0 "

* Intermediate values.

See fig. 8.

Table VI

Initial absorbability: $(\mu/\rho)_{Al}$ = 3.5 nearly		Initial absorbability: μ/ρ = 1.5 nearly	
Thickness of Al.	Secondary/primary	Thickness of Al.	Secondary/primary.
0.0 cm.	1.0 × x	0.0 c.m.	.735 × y
.018 cm.	1.0 "	.009 cm.	.66 "
.027 "	1.0 "	.018 "	.625 "
.036 "	1.0 "	.036 "	.580 "
.045	.93 "	.054 "	.505 "
.054	.91 "	.036 "	.575 "
.063	.909 "	.045 "	.525 "
		.072 "	.475 "
		.09 "	.450 "
		.108 "	.425 "
		.027 "	.590 "

See fig. 9 (a)

Table VII

Initial absorbability: $(\mu/\rho)_{Al}$ = 3.5 nearly.

Number of paper sheets.	Secondary / primary (arbitrary units)
0	.99 × x
10	1.00 "
15	.995 "
20	.99 "
25	.995 "
30	1.00 "
35	.94 "
40	.93 "
60	.92 "

See fig. 9 (b).

Table . VIII

$(\mu/\rho)_{Al} = 1.4$		$(\mu/\rho)_{Al} = 2.6$	
Thickness of Silver	Secondary /primary	Thickness of Silver.	Secondary /primary.
0.0 cm.	1.00 x x	0.0 cm.	1.00 x x
.0021"	1.00 " .95 "	.0021 cm.	1.00 "
.0042"	.95 "	.0042 "	1.00 "
.0063"	.95 "	.0063 "	1.00 "
.0085"	.95 "	.0085 "	1.005 "
.0105"	.90 "	.0105 "	1.00 "
	$(\mu/\rho = .90)$	.0120 "	.95 "
			$(\mu/\rho = 1.4)$
.0120"	.90 x x	.0105 "	1.00 x x
.0085"	.95 "	.0120 "	.95 "
.0141"	.90 "	.0141 "	.95 "
.0162"	.79 "	.0162 "	1.00 " .95 "
	$(\mu/\rho = .79)$		
0.0 cm.	1.0 "	.0183 "	.95 "
.0183cm.	.79 "		
.0120 "	.90 "		

See fig. 10.

Table IX

$(\mu/\rho)_{Al}$ = 1.5 nearly		$(\mu/\rho)_{Al}$ = 1.5 nearly	
Thickness of Tin	Secondary/primary	Thickness of Tin	Secondary/primary
0.0 cm.	.95 x x	0.0 cm.	1.0 x x
.002 "	.92 "	.002 "	1.0 "
.004 "	.91 "	.004 "	1.0 "
.0057 "	.90 "	.0057 "	1.0 "
.0075 "	.89 "	.0075 "	1.0 "
.0100 "	.845 "	.0100 "	.88 ") 1.00 ")
.010 "	.91 "	----------	----------
.0120 "	.90 "	.010 "	.90 "
~~.0120 "~~	~~.90 "~~	.012 "	.90 "
.0140 "	.915 "	.014 "	.91 "
.004 "	.99 "	.0157 "	.90 "
.002 "	1.00 "		
0.0 "	1.00 "		
.0057 "	.99 "		
.0075	.99 " } .915 " }		
.010 "	.90 "		

See fig. 11.

Table X...

Secondary beam filtered		Primary filtered	
Thickness of Al.	I_x/I_0	Thickness of Al.	I_x/I_0
0.0 cm.	1.00 x x	.027 cm.	.835 x x
.009 "	.909 "	.018 "	.884 "
.018 "	.828 "	.027 "	.835 "
.027 "	.772 " .742 "	.036 "	.792 "
.036 "	.707 " .671 "	.045 "	.752 "
.045 "	.636 "	.054 "	.720 "
.054 "	.590 "	.063 "	.691 "
.063 "	.545 "	.072 "	.665 "
.072 "	.515 "	.081 "	.642 "
.081 "	.520 " .474 "	.09 "	.616 "
.090 "	.489 "		
.036 "	.671 "		
.027 "	.772 "		
.036 "	.712 "		

See figs. 12(a) & 12(b).

Table XI

Beams intercepted by different thicknesses of Aluminium.

$(\mu/\rho)_{Al}$ primary	S/P(x = .009cm.)	S'/P'(x = .054cm.)	S'/P'(x = .117 cm.)
2.38	1.0 x x	.91 x x	.81 x x
2.82	1.0 "	.91 "	.82 "
3.12	1.01 "	.92 "	.82 "
2.04	1.0 "	.91 "	.75 "
2.01	.96 "	.86 "	.745 "
1.89	.96 "	.845 "	.75 "
1.81	.97 "	.86 "	.75 "
1.79	.95 "	.85 "	.745 "
1.72	.95 "	.845 "	.745 "

See fig. 13.

Table XII

$(\mu/\rho)_{Al} = 4.0$		$(\mu/\rho)_{Al} = 3.0$	
Thickness of Al.	Secondary/primary	Thickness of Al.	Secondary/primary
0.0 cm.	1.0 x	0.0 cm.	1.01 x
.048 "	1.0 "	.018 "	1.005 "
.048 "	.99 "	----------	----------
.058 "	1.0 "	.027 "	.955 "
----------	----------	.036 "	.94 "
.068 "	.91 "	.054 "	.92 "
.078 "	.87 "	.072 "	.90 "
		.09 "	.875 "

To face fig. 14.

Table XIII

$(\mu/\rho)_{Al} = 2.6$		$(\mu/\rho)_{Al} = 1.6$	
Thickness of Silver	Secondary/primary	Thickness of Silver	Secondary/primary
0.0 cm.	1.0 × x	0.0 cm.	1.0 × x
		.0021 "	1.0 "
.0021 "	1.0 "	----------	----------
.0042 "	1.0 "	.0042 "	.95 "
.0063 "	1.0 "	.0063 "	.955 "
.0085 "	1.005 "	.0085 "	.955 "
.0105 "	1.0 "	.0105 "	.96 "
----------	----------	.012 "	.95 "
.12 "	.95 " $(\mu/\rho = 1.4)$		
.0141 "	.95 "		
.0162 "	1.0 ") .95 ")		
.0183 "	.95 (not plotted)		

To face figs. 15(a) + 15(b).

Table XIV

Thin Celluloid as window of the ionisation chambers		Thin aluminium as window of the ionisation chambers	
$(\mu/\rho)_{Al}$ primary	Secondary/primary	$(\mu/\rho)_{Al}$ primary	Secondary/primary.
1.14	1.01 x x	1.23	.93 x x
1.49	1.0 "	1.38	.93 "
1.90	1.01 "	1.58	.945 "
2.07	1.01 "	1.64	.945 "
2.44	1.0 "	1.68	.945 "
3.31	1.0 " (not plotted)	1.69	.945 "
		1.84	.98 "
		1.99	.99 "
3.65	1.0 x x (not plotted)	2.0	1.00 "
		2.14	1.00 "
		2.58	1.01 "
		2.62	1.0 "
		2.71	1.0 "

To face fig. 16.

Table XV.

Case B.

Aluminium (= .048 cm)		
$(\mu/\rho)_{Al}$ (primary	S/P	S'/P'
1.77	.98 × x	.91 × x
1.83	.98 "	.91 "
1.98	1.00 "	.91 "
2.14	1.00 "	.91 "
2.38	1.00 "	.92 "
2.45	1.00 "	.92 "
2.5	1.00 "	.92 "
3.08	1.00 "	.92 "
3.45	.995"	.92 "
3.55	1.00 "	.92 "
3.77	1.00 "	.92 "
4.61	1.00 "	.92 "

Copper (= .001 cm.)		
$(\mu/\rho)_{Al}$ (primary)	S/P	S'/P'
1.14	1.01 × x	.95 × x
1.49	1.00 "	.94 "
1.90	1.01 "	.95 "
2.07	1.01 "	.95 "
2.44	1.00 "	.94 "
3.31	1.00 "	.94 "
3.65	1.00 "	.94 "
4.41	-	.94 "

Tin (= .002 cm.)		
$(\mu/\rho)_{Al}$ (primary)	S/P	S'/P'
1.25	1.00 × x	1.01 × x
1.58	1.005 "	1.005 "
		.97 "
1.64	1.005 "	1.005 "
		.97 "
2.38	1.01 "	.97 "
2.59	1.005 "	1.005 "
2.65	1.005 "	1.01 "
		.96 "
3.17	.995 "	.99 "
		.96 "
3.35	1.01 "	.96 "
		1.00 "
3.46	1.00 "	.96 "
3.57	1.005 "	1.00 "
		.96 "
3.88	1.01 "	.96 "
4.11	1.01 "	1.01 "
4.7	.99 "	.95 "
4.82	1.00 "	.96 "
5.03	1.00 "	1.00 "
5.17	1.005 "	.96 "
		1.00 "
5.32	1.00 "	1.00 "
		.96 "

Gold (= .0008 cm.)		
$(\mu/\rho)_{Al}$ (primary)	S/P	S'/P'
1.25	1.00 × x	.89 × x
1.58	1.005 "	.90 "
1.64	1.005 "	.90 "
2.38	1.01 "	.90 "
2.59	1.005 "	.915 "
2.65	1.005 "	.90 "
3.17	.995 "	.90 "
3.35	1.01 "	.905 "
3.57	1.005 "	.90 "
3.88	1.01 "	.90 "
4.11	1.01 "	.915 "
4.7	.99 "	.90 "
4.82	1.00 "	.90 "
5.03	1.00 "	.90 "
5.17	1.005 "	1.01 " (not plotted)
5.32	1.00 "	.90 "
		(not plotted)

For diagrams see fig. 17.

Table XVI

Case A. Initial absorbability: $(\mu/\rho)_{Al} = 3.2$ to $3{\cdot}5$		Case B. Initial absorbability: $(\mu/\rho)_{Al} = 3.5$	
Thickness of Al.	Secondary/primary	Thickness of Al.	Secondary / primary
0.0 cm.	1.00 x x	0.0 cm.	1.00 x x
.018 cm.	1.00 "	.009 "	.98 "
.027 "	1.00 "	.018 "	.96 "
.036 "	1.00 "	.027 "	.95 "
.045 "	.93 "	.036 "	.94 "
.054 "	.91 "	.045 "	.92 "
.063 "	.909 "	.048 "	.91 "
		.063 "	.88 "

For diagram, see fig. 18.

Table XVII

Aluminium (Initial absorbability $\mu/\rho_{Al} = 3.6$)		Copper (Initial absorbability $\mu/\rho_{Al} = 3.6$)		Tin (Initial absorbability $\mu/\rho_{Al} = 3.6$)	
Thickness of Al.	$\frac{\text{Secondary}}{\text{primary}}$	Thickness of Cu.	$\frac{\text{Secondary}}{\text{primary}}$	Thickness of Tin	$\frac{\text{Secondary}}{\text{primary}}$
0.0 cm.	1.00 x x	0.0 cm.	1.00 x x	0.0 cm.	.99 x x
.02 "	.96 "			.01 "	.88 "
.04 "	.93 "	.00109 "	.95 "	.002 "	.96 "
.048 "	.915 "	.00222 "	.90 "	.004	.98 " .95 "
.06 "	.90 "	.00337 "	.87 "	.00575 "	.94 "
.08 "	.88 "	.00518 "	.85 "	.010	.99 "
.10 "	.855 "	.00704 "	.82 "	.00575	1.00 "
		.00889 "	.80 "	.002	.97 "

Gold. (Initial absorbability $\mu/\rho_{Al} = 2.2$)

Thickness of Gold	Secondary/primary
0.0 cm.	1.00 x x
.0008 "	.89 "
.00155 "	.82 "
.00233 "	.75 "
.00310 "	.67 "

For diagrams, see figs. 19(a) & (b)

Table XVIII

"Sub-level". Angle of Scattering = 90°

μ/ρ_{Al} (primary)	S/P	S'/P' (Thickness of Al.= .048cm.
1.68	.99 x x	.90 x x
1.73	1.0 "	.91 "
1.88	1.0 "	.91 "
1.96	1.0 "	.91 "
2.01	1.0 "	.91 "
2.26	.99 "	.91 "
2.39	1.005 "	.945 "
2.75	1.00 "	.945 "
2.85	1.00 "	.945 "
2.99	1.00 "	.945 "
3.1	.99 "	.945 "
3.46	1.00 "	.945 "

For diagram see fig. 20.

TABLE. XIX

$(\mu/_{\rho})$ Al = 3·5 nearly in each case.

Case A		Case B		Case A(a) ('sub-level')	
Thickness of Al.	$\frac{\text{Secondary}}{\text{Primary}}$	Thickness of Al.	$\frac{\text{Secondary}}{\text{Primary}}$	Thickness of Al.	$\frac{\text{Secondary}}{\text{Primary}}$
0·0 cm.	1·00 × x	0·0 cm.	1·00 × x	0·0 cm.	1·00 × x
·018 "	1·00 "	·02 "	.96 "	.018 "	1·00 "
·027 "	1·00 "	.04 "	.93 "	.027 "	1·01 "
		·048 "	·915 "		
·036 "	1·00 "	·06 "	·90 "	·036 "	·995 "
·045 "	·93 "	·08 "	·88 "	·045 "	·945 "
·054 "	·91 "	·10 "	·87 "	·054 "	·935 "
·063 "	·909 "			·090 "	·905 "

For diagram see fig. 21.

Table XX

Average mass-absorption-coefficient (in aluminium) of primary radiation = 5.3

Δ	N
-4.5	1
-3.0	7
-1.5	18
0	28
+1.5	17
+3	9
+4.5	1
+6	1
+7.5	1
+9	2
+10.5	5
+12	15
+13.5	20
+15	12
+16.5	10
+18	3
+19.5	1

For diagram see fig. 22.

Table XXI

Aluminium (μ/ρ_{Al} = 3.0) Initial absorbability.		
Thickness of Al.	Secondary / primary	
0.0 cm.	1.00 x	x
.045 "	1.00	"
.054 "	1.00	"
.063	.92	"
.0	.99	"
.045	1.00	"
.063	.99	"
.081	.99	"
.099	1.00	"
0.0	.99	"
.018	1.00	"
.027	.98	"

Paper. (μ/ρ = 3.6) Initial absorbability.		
Number of paper sheets	Secondary / primary	
0	1.01 x	x
10	1.01	"
15	1.01	"
20	1.0	"
25	.995	"
30	.94	"
35	.93	"
40	.93	"
50	.93	"
60	1.0	"
0	1.01	"
30	1.01	"
50	.995	"
40	.98	"

For diagram see fig. 23.

Table . XXII

Angle of Scattering = 90°		θ = 60°		θ = 30°	
μ/ρ	$\left\{100(S/P - S'/P')\right\} / S/P$	μ/ρ	$\left\{100(S/P - S'/P')\right\} / S/P$	μ/ρ	$\left\{100(S/P - S'/P')\right\} / S/P$
6.13	-1.1 (not plotted)	4.31	0	4.77	8.5
5.46	0	3.71	0	4.68	8.5
				4.07	8.6
5.37	0.5	3.57	0	3.78	9.2
4.9	10			3.45	9.1
4.68	0.8	3.44	8.2	3.24	9.0
4.42	0	3.05	10.3	3.18	9.1
4.27	0	2.95	9.7	2.97	9.0
3.79	9.3	2.85	9.8	2.85	8.8
3.37	8.8	2.7	8.2	2.69	9.1
2.99	8.0	2.32	10	2.59	8.7
2.89	8.0	2.06	10	2.21	8.8
2.7	8.0			2.19	8.8
2.55	8.1			2.04	8.8
2.08	8.8			1.92	9.1
				1.70	9.1
				1.68	9.1
				1.32	8.8

For diagram see fig. 24.

Table XXIII

Angle of Scattering = 60° Thickness of intercepting Al. = .048 cm.

Case B			Case B(a) ["Sub-Level"]		
μ/ρ primary	S/P	S'/P'	μ/ρ primary	S/P	S'/P'
2.66	.99 x x	.90 x x	5.03	1.0 x x	.95 x x
2.52	1.00 "	.915 "	4.75	.99 "	.94 "
2.21	.99 "	.91 "	4.46	1.0 "	.945 "
1.95	.98 "	.90 "	4.31	.99 "	.94 "
1.3 (approx.)	.99 "	.91 "	4.22	1.00 "	.945 "
			3.98	1.00 "	.945 "
			3.88	1.005 "	.95 "
			3.76	1.00 "	.945 "
			3.45	1.005 "	.945 "
			3.36	.99 "	.945 "
			3.19	1.00 "	.945 "
			3.0	1.005 "	.95 "
			2.24	1.01 "	.95 "
			2.19	1.02 "	.965 "
			2.08	1.01 "	.965 "
			1.94	1.02 "	.98 "
			1.27 (approx.)	1.02 "	.98 "

For diagrams see fig. 25.

NORMAL J_1-LEVEL
& "SUB-LEVEL"

Table XXIV

Cases B & B(a) Thickness of intercepting Alum. = .048 cm.

θ = 90°			θ = 60°		
μ/ρ	S/P	S'/P'	μ/ρ	S/P	S'/P'
primary			primary		
3.46	1.0 × x	.945 × x	3.17	.99 × x	.91 × x
3.10	.99 "	.945 "	2.85	1.0 "	.95 "
2.99	1.0 "	.945 "	2.45	1.0 "	.95 "
2.85	1.0 "	.945 "	2.30	1.0 "	.95 "
2.75	1.0 "	.945 "	2.21	.995 "	.95 "
2.39	1.005 "	.945 "	1.89	.995 "	.95 "
2.26	.99 "	.91 "	1.73	.995 "	.91 " } .95 " }
2.01	1.0 "	.91 "	1.63	.99 "	.91 "
1.96	1.0 "	.91 "	1.37	.995 "	.92 " } .95 " }
1.88	1.0 "	.91 "			
1.73	1.0 "	.91 "			
1.68	.99 "	.90 "			

For diagrams see fig. 25.

Table XXV

Case B.

$\theta = 90^\circ$		$\theta = 60^\circ$		$\theta = 30^\circ$	
Thickness of Alum.	Secondary / primary	Thickness of Alum.	Secondary / primary.	Thickness of Alum.	Secondary / primary
0.0 cm.	1.00 × x	0.0 cm.	1.00 × x	0.0 cm.	1.00 × x
.048 "	.915 × "	.048 "	.915 "	.048 "	.915 "
.02 "	.96 × "	.02 "	.97 "	.02 "	.955 "
.04 "	.93 × "	.04 "	.94 "	.04 "	.93 "
.06 "	.90 × "	.06 "	.91 "	.06 "	.895 "
.08 "	.88 × "	.08 "	.935 " *	.08 "	.87 "
.10 "	.855 × "	.10 "	.91 " *	.10 "	.85 "
$(\mu/\rho)_{Al}$ = 3.57		.08 "	.93 " *	.135 "	.81 "
		.06 "	.95 " *	$(\mu/\rho)_{Al}$ = 3.02	
		.04 "	.94 "		
		.02 "	.96 "		
		.08 "	.88 "		
		.10 "	.91 " *		
		0.0 "	1.0 "		
		$(\mu/\rho)_{Al}$ = 2.6			

For diagrams See fig. 26.

* These values correspond to Case B(a) ('Sub-level').

N.B. The slope of these curves is independent of the hardness of the radiation as is expected from the result previously obtained:- viz. s'/p' = const. over a long range of wave-lengths.

Table . XXVI

Angle of Scattering = 30^0 Thickness of intercepting alum = .048cm.

$(\mu/\rho)_{Al}$ (primary)	S/P	S'/P'
2.65	1.0 x x	1.0 x x
2.79	1.0 "	1.0 " .93 "
2.93	.93 "	1.0 "
3.02	.93 "	1.0 "
3.19	.93 "	1.0 "

For diagrams see fig. 27.

Table . XXVII

Angle of Scattering = 60^0 Thickness of intercepting Silver = .002cm.

Al. filter	$(\mu/\rho)_{Al}$ primary	S/P	S'/P'	Al. filter	$(\mu/\rho)_{Al}$ primary	S/P	S'/P'
.09 cm.	1.32	1.0 x x	1.05 x x	.137 cm.	1.27	1.01 x x	1.04 x x
"	1.43	1.0 "	1.10? "	.10 "	1.94	1.005"	1.04 "
.04 "	1.58	1.0 "	1.04 "	.08 "	2.08	1.005"	1.04 "
0 "	1.83	1.0 "	1.04 "	.06 "	2.19	1.005"	1.005"
0 "	1.88	1.0 "	1.04 "	.04 "	2.24	1.0 "	1.0 "
0 "	2.22	1.0 "	1.03 "	.02 "	2.98	1.0 "	1.0 "
0 "	2.44	1.0 "	1.03 "	0 "	3.02	.99 "	.99 "
0 "	2.59	.99"	1.0 "	0 "	3.19	.99 "	.99 "

For diagrams see figs. 28(a) &(b).

Table XXVIII (a)

Aluminium (= .050 cm.) $\mu_1/\rho = 12.54\lambda^3 + \sigma/\rho$

$\mu_2/\rho = 12.54(\lambda + .024)^3 + \sigma/\rho$ (Hewlett)[1]

λÅ	$(\mu/\rho)_{Al.}$	S/P (Calc.)	S/P (obs.)	S'/P' (calc.)	S'/P' (obs.)
.30	.51	1.014 x x	- x x	1.002 x x	- x x
.40	.98	1.007 "	-	.985 "	-
.45	1.27	1.007 "	-		-
	1.45	-	1.01 "	-	.92 "
.50	1.85	1.00 "	-	.964 "	-
	1.94	-	1.01 "	-	.91 "
	2.72	-	1.00 "	-	.90 "
.60	3.15	1.004	-	.959 "	-
	3.50	-	.99 "	-	.90 "
	3.85	-	1.00 "	-	.90 "
	4.26	-	1.01 "	-	.91 "
	4.76	-	.98 "	-	.91 "
.70	4.84	1.001	-	.941 "	-
.80	7.26	1.001	-	.926 "	-

For diagram see fig. 30.

N.B. The first two columns are taken from Hewlett.

(1) Hewlett, March 1921, Phys. Rev.

Table XXVIII (b)

Copper (= .001 cm.) $\mu_1/\rho = 153\lambda^3 + \sigma/\rho$ Richtmyer & Warburton.[1]

$\mu_2/\rho = 153(\lambda + .024)^3 + \sigma/\rho$

λ Å	$(\mu/\rho)_{Al.}$	S/P calc.	S/P obs.	S'/P' calc.	S'/P' obs.
.30	.51	1.014 x x	-	1.004 x x	-
.40	.98	1.007 "	-	.990 "	-
	1.14	-	1.01 x x	-	.95 x x
	1.49	-	1.00 "	-	.94 "
.50	1.85	1.00 "	-	.974 "	-
	1.90	-	1.01 "	-	.95 "
	2.07	-	1.01 "	-	.95 "
	2.44	-	1.00 "	-	.94 "
.60	3.15	1.004 "	-	.968 "	-
	3.31	-	1.00 "	-	.94 "
	3.65	-	1.00 "	-	.94 "
	4.41	-	-	-	.94 "
.70	4.84	1.001 "	-	.953 "	-
.80	7.26	1.001 "	-	.939 "	-

See table XV

For diagram see fig. 30.

N.B. The first two columns are taken from Hewlett.

(1) Richtmyer & Warburton, Phys. Rev. Dec. 1923,

Table ..XXVIII (c)

Silver (= .002 cm.) $\mu/\rho = 86\lambda^3 + .6$ (long wavelength side)
$\mu/\rho = 603\lambda^3 + .7$ (short wavelength side)
(Richtmyer & Warburton)

λ Å	$(\mu/\rho)_{Al.}$	$S/P_{calc.}$	$S/P_{obs.}$	$S'/P'_{calc.}$	$S'/P'_{obs.}$
.30	.51	1.014 x x	-	.915 x x	-
.40	.98	1.007 "	-	.857 "	-
	1.68	-	.99 x x	-	.96 x x
	1.73	-	1.00 "	-	.96 "
.50	1.85	1.00 "	-	.775 S .964 L	-
	1.88	-	1.00 "	-	.96 "
	1.96	-	1.00 "	-	.96 "
	2.01	-	1.00 "	-	.96 "
	2.12	-	.99 "	-	1.00 "
	2.38	-	1.0 "	-	1.005 "
	2.5	-	1.0 "	-	.99 "
	2.75	-	1.0 "	-	1.0 "
	2.85	-	1.0 "	-	1.01 "
	3.09	-	.995 "	-	.995 "
.60	3.15	1.004 "	-	.710 "S .956 "L	-
	3.45	-	1.0 "	-	.995 "
	3.55	-	1.0 "	-	.995 "
	3.77	-	1.0 "	-	1.0 "
	4.61	-	.995 "	-	.995 "
.70	4.84	1.001 "	-	.938" L	-
.80	7.26	1.001 "	-	.919" L	-

See Table ..IV..

For diagram see fig. 31.

N.B. The first two columns are taken from Hewlett.

Table ~~.....~~ XXVIII (d)

Tin (= .002 cm.) $\mu/\rho = 90\lambda^3 + 1$ (Long wavelength side)

$\mu/\rho = 575\lambda^3 + 1$ (Short wavelength side)

See table XV (Richtmyer) ~~See Table~~ ......

For diagram see Fig. 31

λ Å	$(\mu/\rho)_{Al.}$	$S/P_{Calc.}$	$S/P_{obs.}$	$S'/P'_{calc.}$	$S'/P'_{obs.}$
.30	.51	1.014 x x	–	.96 x x	–
.40	.98	1.007 "	–	.92 "	–
	1.25	–	1.00 x x	–	1.01 x x
.45	1.27	1.007 "		.89 " S .99 " L	–
	1.58	–	1.005 "	–	1.005 " .97 "
	1.64	–	1.005 "	–	1.005 " .97 "
.50	1.85	1.00 "		.86 " S .98 " L	–
	2.38	–	1.01 "	–	.97 "
	2.59	–	1.005 "	–	1.005 "
	2.65	–	1.005 "	–	1.01 " .96 "
.60	3.15	1.004 "		.97 " L	–
	3.17	–	.995 "	–	.99 " .96 "
	3.35	–	1.01 "	–	.96 " 1. 0 "
	3.46	–	1.00 "	–	.96 "
	3.57	–	1.005 "	–	1.00 " .96 "
	3.88	–	1.01 "	–	.96 "
	4.11	–	1.01 "	–	1.01 "
	4.7	–	.99 "	–	.95 "
	4.82	–	1.00 "	–	.96 "
.70	4.84	1.001 "	–	.95 " L	–
	5.03	–	1.00 "	–	1.00 "
	5.17	–	1.005 "	–	.96 " 1.00 "
	5.32	–	1.00 "	–	1.00 " .96 "

N.B. The first two columns are taken from Hewlett -

Table XXVIII (e)

Gold (= .0008 cm.) $\mu/\rho = 395\lambda^3 + .85$ (Richtmyer)[1]

λ Å	$(\mu/\rho)_{Al.}$	$S/P_{calc.}$	$S/P_{obs.}$	$S'/P'_{calc.}$	$S'/P'_{obs.}$
.30	.51	1.014 x x	-	.973 x x	-
.40	.98	1.007 "	-	.937 "	-
	1.25	-	1.00 x x	-	.89 x x
	1.58	-	1.005 "	-	.90 "
	1.64	-	1.005 "	-	.90 "
.50	1.85	1.00 "	-	.896 "	-
	2.38	-	1.01 "	-	.90 "
	2.59	-	1.005 "	-	.915 "
	2.65	-	1.005	-	.90 "
.60	3.15	1.004 "	-	.854 "	-
	3.17	-	.995 "	-	.90 "
	3.35	-	1.01 "		.905 "
	3.57	-	1.005 "		.90 "
	3.88	-	1.01 "		.90 "
	4.11	-	1.01 "		.915 "
	4.70	-	.99 "		.90 "
	4.82	-	1.00 "		.90 "
.70	4.84	1.001 "	-	.801 "	-
	5.03	-	1.00 "	-	.90 "
	5.17	-	1.005 "	-	1.01 "
	5.32	-	1.00 "	-	.90 "
.80	7.26	1.001 "	-	.751 "	-

See table XV

For diagram see fig. 31.

N.B. The first two columns are taken from Hewlett.

(1) Richtmyer, Phys. Rev. Jan. 1926.

Table XXIX (a)

Case A.

Angle of Scattering = 90°　　　(See Table XXII.)

λ Å	$(\mu/\rho)_{Al.}$	$\frac{100.(S/P - S'/P')}{S/P}$ Calc.	$\frac{100.(S/P - S'/P')}{S/P}$ Obs.
.50	1.85	3.1	-
	2.08	-	8.8
	2.55	-	8.1
	2.7	-	8.0
	2.89	-	8.0
	2.99	-	8.0
.60	3.15	4.5	-
	3.37	-	8.8
	3.79	-	9.3
	4.27	-	0.0
	4.42	-	0.0
	4.68	-	0.8
.70	4.84	6.0	-
	4.9	-	10.0 (not plotted)
	5.37	-	0.5
	5.46	-	0.0
	6.13	-	- 1.1 (not plotted)
.80	7.26	7.5	-

For diagram see fig. 32.

N.B. The first two larger columns are taken from Hewlett.

Table XXIX (b)

Case A

Angle of Scattering = 60°   See Table XXII

λ Å	$(\mu/\rho)_{Al.}$	$100\frac{(S/P - S'/P')}{S/P}$ Calc.	$100.\frac{(S/P - S'/P')}{S/P}$ Obs.
.50	1.85	1.4	-
	2.06	-	10.0
	2.32	-	10.0
	2.7	-	8.2
	2.85	-	9.8
	2.95	-	9.7
	3.05	-	10.3
.60	3.15	2.3	-
	3.44	-	8.2
	3.57	-	0.0
	3.71	-	0.0
	4.31	-	0.0
.70	4.84	3.0	-
.80	7.26	4.0	-

For diagram see fig. 32.

N.B. The first two columns are taken from Hewlett.

Table XXIX (c).

Case B

Angle of Scattering = 30°   See Table XXII

FOR DIAGRAM SEE FIG. 32.

λ Å	$(\mu/\rho)_{Al.}$	$100.\frac{(S/P - S'/P')}{S/P}$ Calc.	$100\frac{(S/P - S'/P')}{S/P}$ obs.
.40	.98	0.3	
	1.32	-	8.8
	1.68	-	9.1
	1.70	-	9.1
.50	1.85	0.4	-
	1.92	-	9.1
	2.04	-	8.8
	2.19	-	8.8
	2.21	-	8.8
	2.59	-	8.7
	2.69	-	9.1
	2.85	-	8.8
	2.97	-	9.0
.60	3.15	0.6	-
	3.18	-	9.1
	3.24	-	9.0
	3.45	-	9.1
	3.78	-	9.2
	4.07	-	8.6
	4.68	-	8.5
	4.77	-	8.5
.70	4.84	0.8	-
.80	7.26	1.0	-

N.B. The first two columns are taken from Hewlett.

Table XXX

Initial absorbability: $(\mu/\rho)_{Al} = 2.7$

Initial absorbability: $(\mu/\rho)_{\cdot} = 3.57$ (3·57)

Additional Silver (.002cm.)			Additional Tin (.002cm.)		
Thickness of Alum.	(S'/P') Al.	(S'/P') Al.&Ag.	Thickness of Alum.	(S'/P') Al.	(S'/P') Al.&Sn.
0.0 cm.	.99 x x	.99 x x	0.0 cm.	1.00 x x	.96 x x
.02 "	.955 "	.96 "	.048 "	.915 "	.915 "
.04 "	.925 "	.92 "	.10 "	.855 "	.855 "
.05 "	.915 "	.91 "	.08 "	.88 "	.885 "
.06 "	.90 "	.90 "	.06 "	.90 "	.90 "
.08 "	.87 "	.87 "	.04 "	.93 "	.93 "
.10 "	.855 "	.86 "	.02 "	.96 "	.93 "
.118 "	.84 "	.84 "			

For diagram see fig. 33(a)

Table XXXI

Initial absorbability: $(\mu/\rho)_{Al} = 2\cdot7$

Number of paper Sheets	(S'/P') paper	(S'/P') paper & silver	S'/P' (PAPER & ALUM)
0	1.00 x x	1.00 x x	.95 x x
10	.99 "	.99 "	.93 "
20	.975 "	.975 "	.915 "
30	.96 "	.96 "	.90 "
50	.94 "	.94 "	.89 "
70	.93 "	.93 "	.88 "

case B(a) "Sub-level"

For diagram see fig. 33 (b)

Table XXXII

$(\mu/\rho)_{Al}$	S/P	(S'/P') Al. (.048 cm.)	(S'/P') Ag. (.002 cm.)	(S'/P') Al. & Ag.
primary				
2.51	.985 x x	.91 x x	.98 x x	.91 x x
2.34	1.0 "	.915 "	.99 "	.915 "
2.16	1.0 "	.915 "	1.0 "	.915 "
2.07	1.0 "	.915 "	1.0 "	.915 "
1.96	1.0 "	.915 "	.965 "	.89 "
1.78	1.0 "	.915 "	.965 "	.88 "

For diagram see fig. 34.

Table XXXIII

$(\mu/\rho)_{Al}$ (primary)	S/P	(S'/P') Al. (.048 cm.)
5.97	.99 x x	1.01 x x
5.54	1.01 "	1.015 "
4.79	.99 "	.98 "
4.75	1.00 "	.98 "
4.5	1.00 "	1.00 "
4.08	1.06 "	1.015 "
3.74	1.06 "	.97 "
3.51	1.06 "	.92 "
3.15	1.06 "	.91 "
3.02	1.06 "	.90 "
2.77	1.06 "	.90 "
2.53	1.06 "	.91 "
2.36	1.05 "	.91 "

For diagram see fig. 35.

Table XXXIV

Unfiltered			filtered through .037 cm. of Alum.		
$(\mu/\rho)_{Al}$ primary	S/P	$(S'/P')_{Sn.}$ x = .002cm.	$(\mu/\rho)_{Al}$ primary	S/P	$(S'/P')_{Sn.}$ x = .002 cm.
3.57	1.0 x x	.96 x x	2.85	.96 x x	.96 x x
2.65	1.0 "	.96 "	2.24	.96 "	.96 "
2.52	1.0 "	.96 "	2.35	.96 "	.96 "
2.32	1.0 "	.96 "	2.04	.96 "	.96 "
2.07	1.0 "	.96 "	1.78	.96 "	.96 "
1.93	1.0 "	.96 "	1.58	.96 "	.96 "
1.90	1.0 "	.96 "	1.49	.96 "	.96 "
1.64	1.0 "	.96 "	1.26	.97 "	.96 "

For diagram see fig-36.

PUBLISHED PAPERS.

1. The J-transformation of Scattered X-rays.
By BARKLA & KHASTGIR Phil. mag. Jan. 1925

2. The J-phenomenon in X-rays—(Part II) Application to Scattered X-rays, By Barkla & Khastgir.
Phil. mag. Nov. 1925.

3. The "modified Scattered" X-radiation, by Barkla & Khastgir
Nature, Feb. 13, 1926

4. Spectroscopic Evidence of J-transformation of X-radiation, by Khastgir & Watson, Nature, April 25, 1925.

I

From the PHILOSOPHICAL MAGAZINE, vol. xlix. *January* 1925.

THE J TRANSFORMATION OF SCATTERED X-RAYS.

BY

C. G. BARKLA, F.R.S.,

AND

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From the PHILOSOPHICAL MAGAIZNE, vol. xlix. *January* 1925.

The J Transformation of Scattered X-Rays. *By* C. G. BARKLA, *F.R.S., and* S. R. KHASTGIR, *Ph.D., University of Edinburgh.*

SINCE the earliest experiments on the scattering of X-rays it has been known that certain condtions were necessary in order to obtain *evidence* of the purest scattering of X-radiation. Under these conditions, through a wide range of wave-lengths, the secondary radiation did not differ appreciably in penetrating power from the primary. It was *this* secondary radiation, and no other, which was called the scattered X-radiation ; it was this which we showed could be explained in its polarization, in its distribution, in its intensity, precisely by the application of the classical theory as given by J. J. Thomson. (It gave exactly the number of extra-nuclear electrons per atom.) In the experimental investigations it was observed or arranged that the complications appearing under other conditions were not introduced.

Under other conditions—conditions which appear to have been obtained by many experimenters on the subject—there was a marked difference between the primary and secondary radiation *as observed.* (See Phil. Mag. April 1923 : Barkla and Mrs. Sale.) Whatever the explanation—there were several possibilities—this secondary radiation was obviously something different from the scattered radiation. This, however, has *also* recently been called by Compton the scattered radiation, and the classical theory of scattering has then been described as inadequate. As the classical theory of scattering was intended only to explain scattering, it is not surprising that it does not cover the other phenomenon which has been given the same name.

This phenomenon has been briefly discussed by one of us in a letter to 'Nature' †, and more fully in a lecture to the Röntgen Society ‡, and its application to the scattering of X-rays has been indicated. A fuller treatment of the subject will appear in other papers, but we propose to give a short description of one only of a series of experiments showing how the true nature of the phenomenon of scattering has in many cases been obscured.

Preliminary results of the kind described in this paper

† November 17, 1923.

‡ A summary only has been published in 'Nature,' November 22, 1924. A more detailed account will be given in the Journal of the Röntgen Society.

were obtained by Barkla and Mrs. Sale several years ago (1921–22); but they were so new, so puzzling, that they were withheld from publication for more careful and critical examination. The results were these:—When primary and secondary rays were compared by their power of penetrating thin absorbing sheets, they appeared practically identical; but thicker absorbing sheets showed a most decided difference (about 12 per cent. in absorption coefficient).

Again, it was found necessary to use thin radiators to obtain scattered rays like the primary throughout a long range of wave-lengths. This is indicated on p. 747 *. "When thin sheets of paper were used as the scattering substance—in which case trouble due to differential absorption of primary and secondary beams in the radiating substance was avoided—experiments showed that the scattered was identical with the primary radiation throughout almost the whole range of wave-lengths experimented upon." The complication evidently introduced by thick radiating sheets was purposely avoided in order to obtain the conditions most favourable to the study of fundamental processes.

The experiment described below showed, as in many previous experiments, that the secondary radiation from paper was originally exactly like the primary radiation in penetrating power. When secondary and primary radiations were transmitted through equal thin sheets of aluminium, this equality of penetrating powers persisted only up to a certain critical thickness of absorbing material. An abrupt absorption of the secondary radiation then occurred, and the transmitted radiation was subsequently more absorbable than the primary radiation which was transmitted through exactly the same thickness of aluminium.

Thus the scattered X-radiation was modified by the J phenomenon quite outside the scattering substance, and afterwards appeared as what A. H. Compton regards (presumably) as the quantum scattered radiation. As we have said previously, the phenomenon here has no connexion with the *process* of scattering. Its association with the scattered radiation is quite accidental,—in the sense that it is not fundamental,—for an exactly similar phenomenon may be shown with a primary radiation.

Experiment.

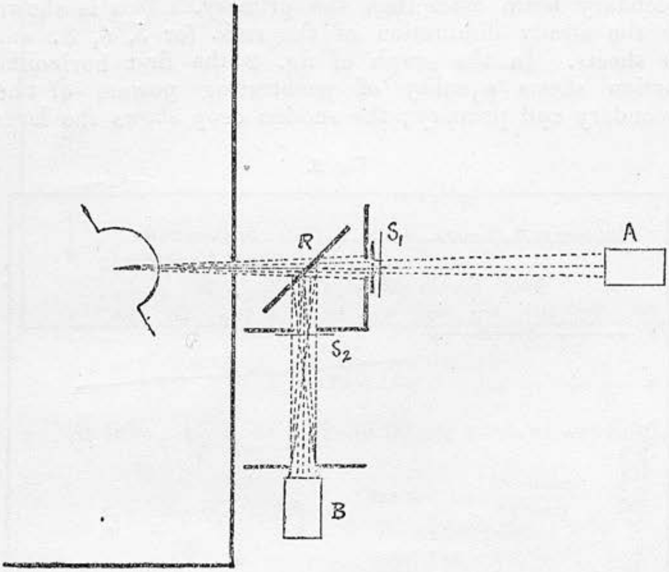
The experiment was quite a simple one. A and B were two ionization chambers—one, A, receiving pencils of

* Phil. Mag. April 1923.

primary radiation; B receiving radiation scattered from the paper sheets R (fig. 1).

The ratio $\frac{\text{Ionization in B}}{\text{Ionization in A}}$ was determined. Thin similar sheets of aluminium were placed at S_1 and S_2, and the above ratio was observed for each thickness of aluminium.

Fig. 1.



The relation between thickness of aluminium and this ratio is shown in Table I. and is represented graphically in fig. 2.

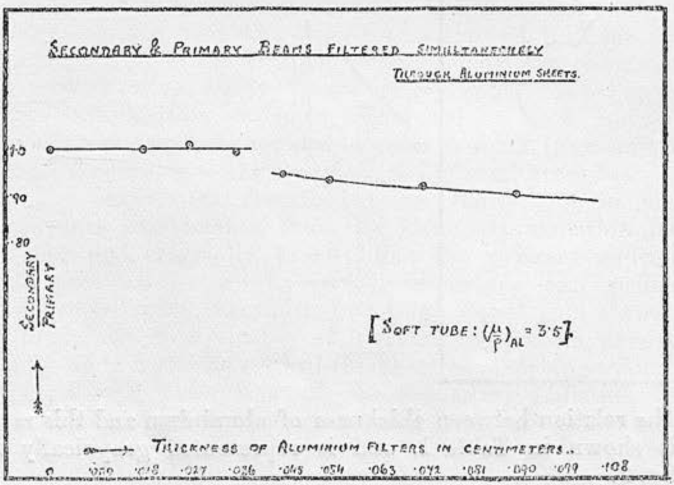
TABLE I.

Soft tube: $\left(\frac{\mu}{\rho}\right)_{Al} = 3{\cdot}5$ (from 50 per cent. absorption).

Thickness of Al filters.	Observed ratio $\frac{\text{Secondary}}{\text{Primary}}$ (in arbitrary units).
0·0 cm.	1·00 $\times x$
·018 „	1·00 „
·027 „	1·01 „
·036 „	·99(5) „
·045 „	·94(5) „
·054 „	·93(5) „
·072 „	·92 „
·090 „	·90(5) „

With 2, 3, and 4 sheets the ratio remained unchanged, showing a very exact equality in penetrating powers and thus in wave-lengths of the primary and secondary radiations. The fifth sheet (giving a total thickness of ·45 millimetre) produced a very big absorption of the secondary beam, as shown by the ratio suddenly dropping from 1·00 to 0·94(5). Subsequent sheets absorbed the secondary beam more than the primary. This is shown by the steady diminution of the ratio for 5, 6, 8, and 10 sheets. In the graph of fig. 2 the first horizontal portion shows equality of penetrating powers of the secondary and primary; the sudden drop shows the large

Fig. 2.



absorption of energy of the secondary beam, and the slope of the curve to the right shows the transformation which has been produced by transmission through the aluminium. The particular sheet at which the transformation occurs depends upon the original penetrating power of the radiation. With harder radiations the discontinuity is displaced to the left of the figure (see fig. 3 and Table II.), and with softer radiations to the right; for the transformation seems to occur when a certain average penetrating power is reached—in this case by filtering. Indeed, with a more penetrating radiation the discontinuity is lost sight of, for even the first thin sheet of absorbing material shows that the difference between the primary and secondary radiations has already been produced. Under such conditions the true nature of the phenomenon is concealed.

Fig. 3.

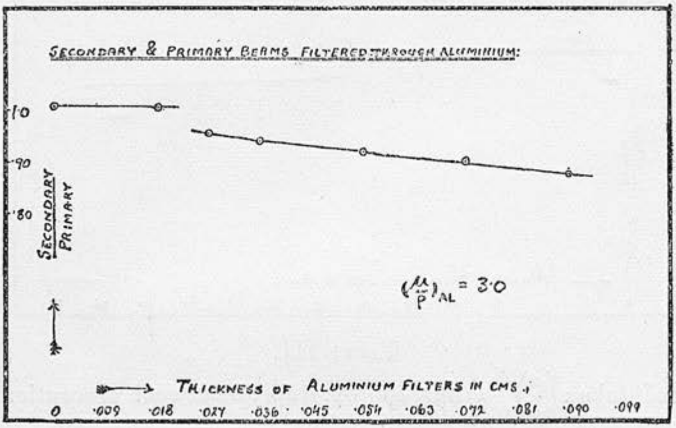


TABLE II.

Soft tube: $\left(\frac{\mu}{\rho}\right)_{Al} = 3$ (from 50 per cent. absorption).

Thickness of Al filters.	Observed ratio $\frac{\text{Secondary}}{\text{Primary}}$ (in arbitrary units).
0·0 cm.	1·01 $\times x$
·018 ,,	1·00(5) ,,
....	....
·027 ,,	·95(5) ,,
·036 ,,	·94 ,,
·054 ,,	·92 ,,
·072 ,,	·90 ,,
·090 ,,	·87(5) ,,

Similar discontinuities have been obtained by filtering the radiations both by paper and by copper. Fig. 4, plotted from the results of Table III., show the corresponding phenomenon in paper. Experiments show that it is necessary to cut off a little more by aluminium than by paper to give the discontinuity—a result perfectly consistent with the conclusions from experiments of a different kind.

Fig. 4.

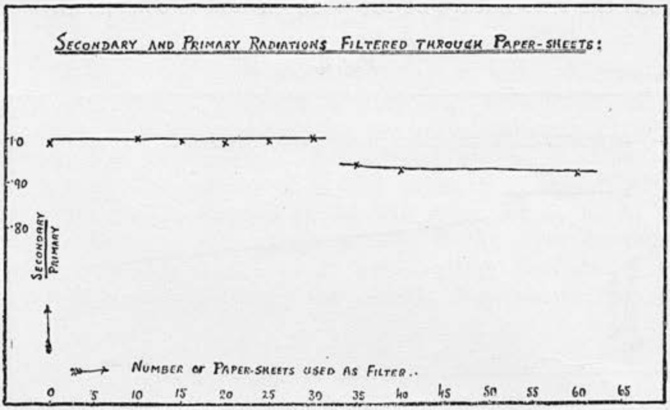


TABLE III.

Soft tube : $\left(\frac{\mu}{\rho}\right)_{Al}=3{\cdot}5$ (approx. from 50 per cent. absorption.)

Number of Paper-sheets.	$\frac{\text{Secondary}}{\text{Primary}}$ (in arbitrary units).
0	·99 × x
10	1·00 ,,
15	·99(5) ,,
20	·99 ,,
25	·99(5) ,,
30	1·00 ,,
....	....
35	·94 ,,
40	·93 ,,
60	·92 ,,

These are only a few of a very large number of experimental results illustrating the "J" phenomenon. This has been briefly described elsewhere, and is receiving fuller treatment in a series of papers. In the case described above, it was the secondary radiation which exhibited the J phenomenon.

Our present purpose in taking this experimental result from its context is to show that the transformation in the secondary radiation has not been produced in the process of scattering. Scattering followed the classical laws; the J transformation gave the appearance of a change of wave-length in scattering.

As previously stated, the J process is probably governed by quantum laws—but it is quite distinct and fundamentally different in origin and nature from the process of scattering.

II

From the Philosophical Magazine, *vol.* 1. *November* 1925.

THE J PHENOMENON IN X-RAYS.—PART II. APPLICATION TO SCATTERED X-RAYS.

BY

C. G. BARKLA, F.R.S.,

AND

S. R. KHASTGIR, Ph.D.,

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From the PHILOSOPHICAL MAGAZINE, vol. 1. *November* 1925.

The J Phenomenon in X-Rays.—Part II. *Application to Scattered X-Rays.*

By C. G. BARKLA, *F.R.S.*, *and* S. R. KHASTGIR, *Ph.D.*, *University of Edinburgh.*

Introduction.

THE recent publication † of a preliminary account of the J phenomenon in X-rays enables us to give an intelligible account of many phenomena associated with scattered X-rays. Such phenomena have recently received a great deal of attention, partly because the well-known difference sometimes appearing between primary and scattered X-rays has been observed by the X-ray spectrometer, and partly because of the daring hypothesis put forward by A. H. Compton to explain these experimental results.

Before discussing this work it is not inappropriate to say a few words on our experimental methods. There are very many advantages in identifying X-radiation by its penetrating power or, by what is more convenient to express, its absorbability. In investigating fundamental phenomena the method seems in many respects immensely superior to the spectroscopic method—indeed, the absorption method becomes a necessity, for in certain regions wave-length fails to define a radiation; absorbability becomes more fundamental.

The following advantages of the absorption method may be noticed:—

(1) Great accuracy may be obtained in the detection and measurement, not of the absorption-coefficients themselves, but of differences or changes of absorption-coefficients. Indeed, it appears that much higher accuracy can be obtained than by the spectroscopic measurements.

(2) The absorption experiments are much simpler, and, as the results will show, are probably much less liable to misinterpretation.

(3) The processes taking place are capable of detailed examination; the whole apparatus may be easily modified and the important parts be dissected so that changes in the scattering substance, in the absorbing substance, and in the detecting apparatus may be studied in detail. This is not possible with the X-ray spectrometer, for with this comparatively huge masses of scattering substance must be used, and the radiation must pass through thick layers of crystal

† Barkla, Phil. Mag. May 1925.

before its effect can be observed. Transmission through matter is assumed to affect only the intensity.

(4) In the absorption method the experimental conditions may be so varied and the results may be obtained so rapidly, that the ground covered is enormous in comparison with that possible with the X-ray spectrometer. (It is doubtful if the results already obtained upon the J phenomenon could have been obtained in a century's work with the spectrometer.)

(5) The absorption method, too, gives the results of experiments of short duration; whereas in many cases the results of spectroscopic work are simply the average over long periods during which changes may have, and as we shall show probably have, occurred.

(6) By the absorption method, effects may be observed which could never be detected by the X-ray spectrometer because, as we have found, X-ray phenomena are not governed by mere wave-length. In fact, for the investigation of such new phenomena few instruments could be more unsuitable than the X-ray spectroscope. It fetters the observer experimentally; its use assumes much. New and fundamental facts must still be discovered by simple and somewhat primitive methods. Some of the finer developments may come later from spectroscopic observations. Our purpose in this paper is to show that the phenomena appearing in the investigation of scattered X-radiation are merely instances of the much more general J phenomenon, and to give further information regarding this phenomenon before proceeding to a consideration of its nature and meaning.

Direct Comparison of Primary and Scattered Radiations.

A series of measurements of the absorption coefficients of primary and of secondary X-radiations—the latter emitted by paper—was made by Barkla and Mrs. Sale *. These showed very definitely that when soft (low frequency) primary radiations were used the scattered radiation was, within the limits of experimental error, like the primary. There certainly was not a difference in absorption-coefficient of as much as 3 per cent. or in wave-length of 1 per cent. between the two radiations. (Compton's hypothetical difference would range from 3 to 5 per cent. in wave-length.) As the wave-length of primary radiation was reduced, there suddenly appeared—that is at a certain critical

* Phil. Mag. April 1923.

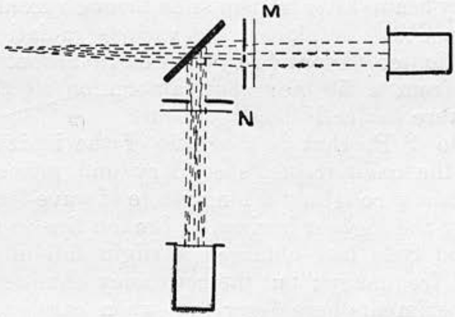
absorption-coefficient—a large difference between the secondary and the primary as usually measured. The secondary radiation abruptly became "softer" than the primary, and the percentage difference became more marked as the wavelength was reduced. It was pointed out at the time that this sudden appearance of a change in the absorption-coefficient of the scattered radiation might be accounted for by the J phenomenon. This has been fully confirmed by more recent experiments. The direct measurements of Barkla and Sale have been repeated and verified, but our results by this method add nothing to those given in their paper. Much greater accuracy, however, has since been obtained, not by measuring the absorption-coefficients of both primary and secondary beams and then comparing these, but by observing more directly any *difference* which may appear between the primary and secondary radiations, as the following description will show.

Difference between Primary and Scattered Radiation.

The method adopted, which proved to be very accurate and yielded some of the most instructive results, was as follows :—

The ratio of the ionizations produced in two similar electroscopes (see fig. 1), one by the secondary radiation from paper

Fig. 1.



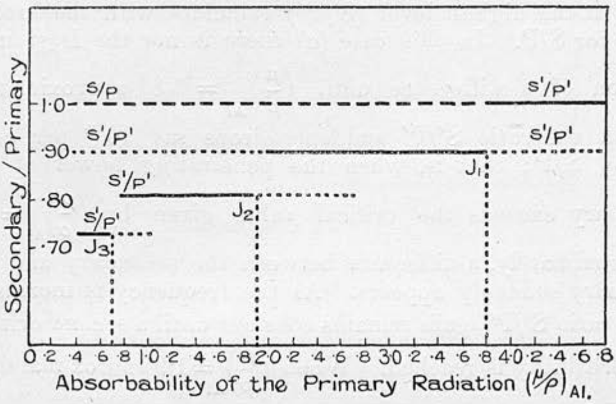
proceeding in a direction at right angles to the primary, and the other by the primary beam or, rather, by fine pencils of the primary radiation, from various portions of the primary beam, was obtained. This ratio $\frac{\text{“ secondary ionization ”}}{\text{“ primary ionization ”}}$, or $\frac{S}{P}$, was usually very constant, the variations amounting to only about 1 per cent. Similar absorbing sheets of aluminium or other substance were placed at M and N in the paths of these two beams on their way to the electroscopes, and the ratio of ionizations was again determined: call it S′/P′. An unchanged ratio of course indicated equal absorptions of secondary and primary radiations; a fall in the ratio indicated that the secondary was the more absorbable. What was observed was either an exact equality or a well-marked difference between the two; *i. e.*, S′/P′ was either equal to or markedly less than S/P. The change from equality to inequality, which was produced by various means, was very abrupt; it was found to be marked by the J discontinuity as observed in other experiments (see Phil. Mag. May 1925).

The ratio S′/P′ of course depended upon the thickness of the absorbing sheets, but the greatest sensitivity and accuracy were obtained by using a thickness which diminished the ionization by about 50 per cent. A difference between S/P and S′/P′ of 1 per cent. would indicate a difference of absorption-coefficients of secondary and primary of about 1·4 per cent. corresponding to a difference of wave-length of less than 0·5 per cent. In any one experiment, however, it is important to notice the thickness of intercepting sheets was kept constant throughout the whole range of radiations experimented upon. The results of a very large number of experiments of this kind are all represented by fig. 2, in which the ratio of ionizations produced by the secondary and primary beams after transmission through fixed absorbing sheets (viz. S′/P′) is plotted for various radiations against the absorption-coefficient (μ/ρ) of each radiation, this being measured from a 50 per cent. absorption as though the radiation were perfectly homogeneous.

The ratio S/P, that is the ratio of the ionizations produced by the *unintercepted* secondary and primary beams, was a constant throughout a long range of wave-lengths; this is shown by the highest horizontal broken line in the figure. (Barkla and Sale had obtained a slight fall of ratio with increase of frequency; but the constancy obtained throughout the experiments here described, when care was taken to eliminate stray radiations, was so marked that we cannot but regard this as expressing the truth, and the small slope obtained previously as being possibly not due to a primary action at all. Be that as it may, the constancy of ratio is the feature to be emphasized; deviations from that, though quite real in the particular experiments referred to, are, as an expression of fundamental actions, suspect; and in any case they are small.)

The constancy might of course be due to a balance of two opposing variations, an increase in the frequency of the primary being accompanied by diminished intensity of secondary radiation combined with increased absorbability and ionizing power compared with the primary. *A priori* such a balance is improbable; the constancy is so marked that it indicates not an approximate balance, but rather a definite absence of variation of either. However, the point is settled without any ambiguity by the results of the experiments, in which both primary and secondary beams were intercepted by absorbing sheets.

Fig. 2.



Broken line - - - - - - - is "unintercepted ratio" S/P.
Continuous line ——— is "intercepted ratio" S′/P′.
Dotted line .... is occasional "intercepted ratio" S′/P′.

The ratio S′/P′—that is, the corresponding ratio obtained when both secondary and primary beams were transmitted through constant equal thicknesses of aluminium (say)—was either precisely the same as S/P or very widely different. Two cases must, however, be described, for all the results obtained throughout a very extensive series of experiments with apparatus of various forms, various X-ray tubes, various ionization chambers, etc., are all included in these two cases, *a* and *b*. These, then, are alternative results, either of which may appear; but the controlling condition has not yet been identified. It seems that the two apparently different results are really fundamentally governed by the same laws. Both are described below and are illustrated graphically in fig. 2. Briefly they are (*a*)—equality of absorption coefficients of primary and secondary over a long range of low frequencies, with well marked differences appearing abruptly at higher frequencies; (*b*)—a constant difference of absorption coefficients of primary and secondary throughout the whole range of frequencies, with no discontinuity over this range.

CASE *a*.

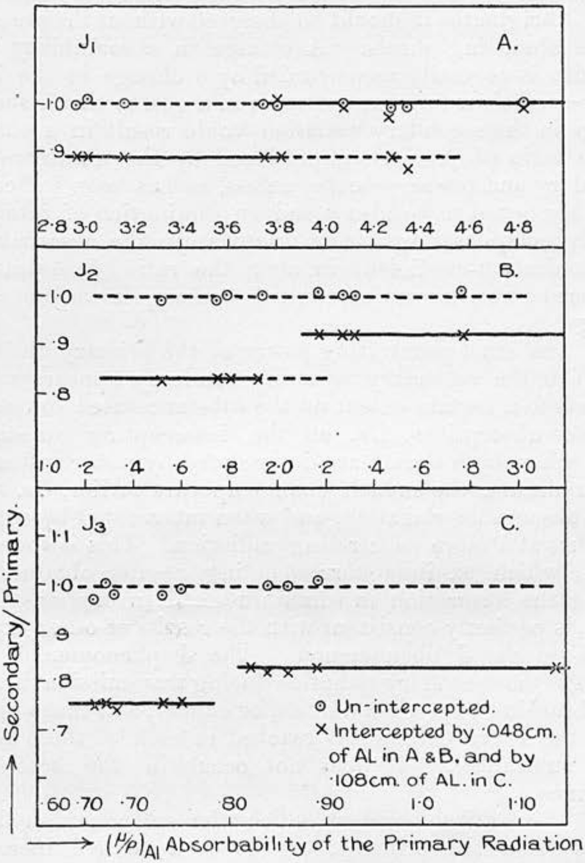
Beginning with soft radiation for which $\left(\frac{\mu}{\rho}\right)_{Al} = 10$ (say), or the wave-length is about ·8 Å.U. and gradually increasing the frequency, that is moving from right to left of fig. 2, the ratio $S'/P' = S/P$ very exactly, and it remains so as the frequency of radiation increases; *i. e.*, the continuous line at the highest level (S'/P') coincides with the broken line for S/P. In this case (*a*) there is not the least indication of a difference until $\left(\frac{\mu}{\rho}\right)_{Al} = 3{\cdot}8$ approximately when the ratio S'/P' suddenly drops say 10 * per cent below S/P; that is, when the penetrating power of the primary exceeds the critical value given by $\left(\frac{\mu}{\rho}\right)_{Al} = 3{\cdot}8$ approximately, a difference between the secondary and the primary suddenly appears. As the frequency is increased, this ratio S'/P' again remains constant until a second critical absorbability is reached. When $\left(\frac{\mu}{\rho}\right)_{Al} = 1{\cdot}9$ approximately, a further drop in ratio S'/P' occurs, and for higher-frequency radiations this ratio again remains constant until a third critical point is reached, $\left(\frac{\mu}{\rho}\right)_{Al} = 0{\cdot}7$, when there is a further drop of ratio S'/P'. Thus, while there is equality of penetrating powers of secondary and primary for soft radiations, there appear these sudden changes in the penetrating power of a secondary beam (as usually measured) at these critical absorbabilities, and when the primary radiation is of short wave-length, the difference between primary and secondary becomes very great indeed.

The values of the ratio S'/P' all fall upon four continuous horizontal lines, the three steps from one level to another being marked J_1, J_2, J_3. Proceeding from low to high

* The precise amount depends on the thickness of aluminium used to intercept both beams; 10 per cent. is approximately the value for a thickness ·05 cm.

frequencies, that is moving from right to left of fig. 2, very occasional values were obtained at the lower level before the J discontinuity was definitely reached. These are shown by dotted lines to the right of the continuous lines*. Examples of the actual observations showing the three discontinuities are given in fig. 3. In this the circles represent "unintercepted

Fig. 3.



ratios" S/P; the crosses give the corresponding "intercepted ratios" S′/P′. Two of the lower occasional values for S′/P′ are shown before the J_1 discontinuity definitely occurred.

* The highest continuous line S′/P′ as shown on the figure is only a very small portion of a long line of observations showing equality of S′/P′ with S/P and stretching to the right of the figure.

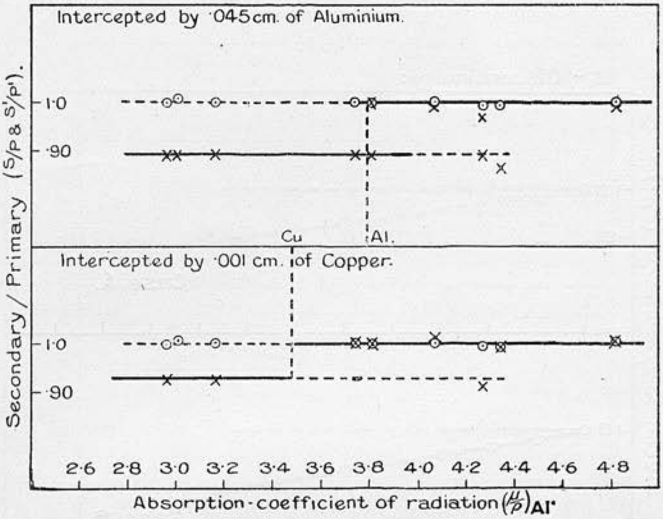
Thus, using any one definite thickness of absorbing substance, the secondary radiation appears softer, *i.e.* more absorbable than the primary, by a series of jumps which occur at the absorption-coefficients, now well known as giving the J discontinuities. This apparent change in the character of the radiation produced by scattering is, however, not what it superficially appears to be, for (1) if it were a true change in the absorbability of the secondary radiation, when it originates it should be observed without the presence of the absorbing sheets. A change in absorbability of a radiation is normally accompanied by a change in the ionization-coefficient for that radiation in a gas, so that a sudden change in the secondary radiation would result in a change in the ratio of ionizations produced by the unintercepted secondary and primary beams unless, as has been indicated, there happened to be also a sudden diminution of intensity exactly compensating for an increase in the absorbability and ionization-coefficient in air; the ratio of ionizations produced by the unintercepted beams shows no such change.

(2) The exact penetrating power of the primary radiation at which the secondary radiation suddenly appears softer, depends to a certain extent on the substance used to test the relative absorptions, *i.e.* on the intercepting substance. Thus, when both beams are intercepted by paper instead of by aluminium, the sudden change appears earlier, *i.e.* for a more absorbable radiation, and when intercepted by copper, it occurs at a more penetrating radiation. This is shown in fig. 4, which exhibits corresponding results obtained by testing the absorption in aluminium and in copper. This, again, is perfectly consistent with the results of other experiments on the J phenomenon. The J phenomenon here occurs in the secondary radiation during transmission through the absorbing paper, aluminium, or copper, and thus appears when the J_1 critical point is reached in each of these absorbing substances. It does not occur in the scattering substance.

(3) The critical point at which the secondary suddenly differs from the primary, or shows a sudden increased difference from the primary, depends upon the thickness of the absorbing sheets used to test the absorbability. When thick absorbing sheets are used, the change appears earlier than with thin absorbing sheets, which, again, is perfectly consistent with the laws observed for the J phenomenon. It simply means that when a thick absorbing sheet is used, the heterogeneous X-radiation becomes filtered until the

average absorption-coefficient reaches or passes the critical value for the J phenomenon, while the thin absorbing sheets do not sufficiently change the average absorption-coefficient to take the beam beyond the critical point. In order to do this the radiation must be a little harder than is the case with the thicker absorbing sheet.

Fig. 4.

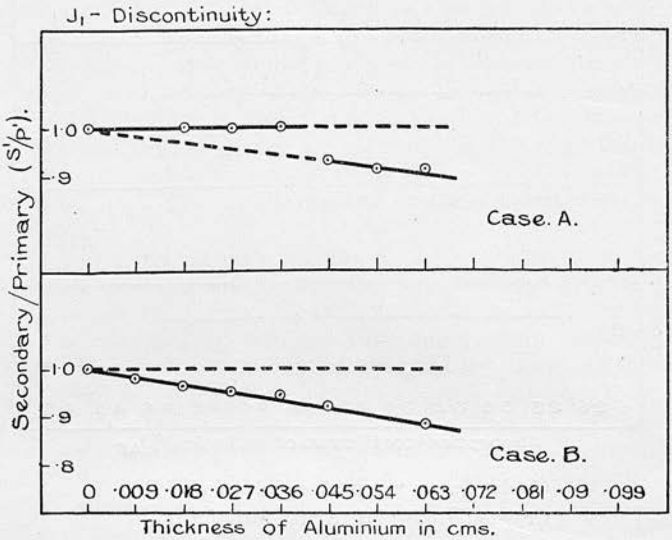


Circles denote "unintercepted ratio" S/P.
Crosses denote "intercepted ratio" S′/P′.

(4) This is most clearly shown by the more direct experiment of keeping the primary radiation unchanged, and gradually increasing the thickness of the absorbing sheets placed in the paths of both primary and secondary radiations, but keeping this thickness the same in the two beams. For when the radiation is somewhat more absorbable than the critical value for the J discontinuity, the thin absorbers indicate no difference between the two, that is S′/P′ is precisely equal to S/P. But as the thickness of the absorber is increased, the critical absorbability is reached by the process of elimination of the softer constituents, and the difference between the secondary and primary radiations suddenly appears in the form of the J discontinuity in the scattered radiation, but not in the primary radiation. Thus,

plotting S′/P′ for different thicknesses of absorbing aluminium, as in fig. 5, Case *a*, the value remains constant until the J_1 step is reached, showing that up to this point the secondary and primary radiations are equally absorbable. The value of S′/P′ then drops suddenly, and subsequently diminishes with increase in the thickness of absorbing aluminium, showing the secondary to be then more absorbable than the primary. Thus for such selected radiations thin absorbers showed no difference between scattered and primary

Fig. 5.

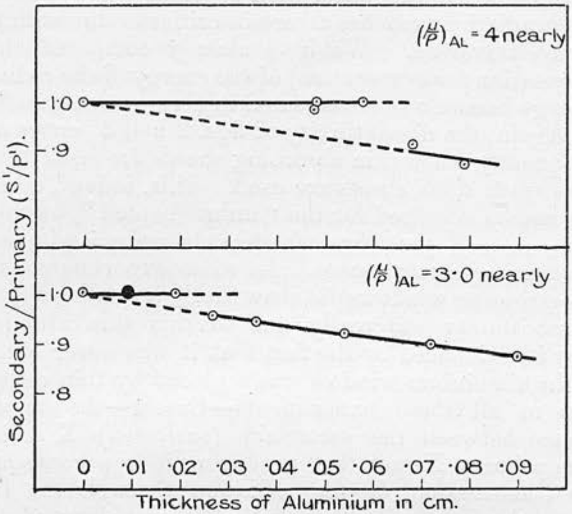


radiations; thick absorbers showed the difference, the latter being separated from the former by the occurrence of the J phenomenon in the absorbing substance.

(5) The magnitude of the sudden fall in the value of S′/P′ depends upon the thickness of absorbing substance already traversed before the discontinuity occurs. Thus, when only a thin sheet was necessary to bring the secondary radiation to its critical absorbability, the drop in the value of S′/P′ was small. When the radiation was absorbable and a thicker sheet was necessary to produce the J discontinuity, the value of S′/P′ fell by a greater amount. In fact, the discontinuity so measured depended in magnitude upon the thickness of absorbing material previously traversed. This was shown both by experiments described above in section (3)—for the

level of the line depends on the thickness of the intercepting sheet—and by the simple filtering experiments. The latter is clearly shown in fig. 6, which brings out the feature that when the discontinuity occurs its magnitude is such as to compensate for what might, under different conditions, have taken place in the absorbing substance already traversed. Thus the sloping portion to the right of the discontinuity is the latter portion of a sloping line starting from the origin. In Case *b*, considered below, in which the J phenomenon did

Fig. 6.



not occur, a difference between the values of S′/P′ and S/P occurred even with the thin sheets (fig. 5, Case *b*). Here the secondary was definitely more absorbable than the primary from the very beginning, but in Case *a*, which we are considering, such a difference between the secondary and primary radiations existed only after the J discontinuity. Such a result suggests that either the last layer of the absorbing sheets necessary to produce the discontinuity precipitates a change which has already been made possible by transmission through the first layers and remains latent until some essential condition is produced, or that the processes taking place in the last layer influence the behaviour of the radiation in the preceding layers; that is, operate backward and cause the earlier layers to absorb more strongly than they do in the absence of that last critical layer.

As a preliminary investigation of this point, *i.e.* as to whether the last effective layer influences the action of preceding layers, we separated the absorbing sheets to considerable distances apart, but we found the result unaffected. Though this experiment is not conclusive, we are inclined to regard the last layer as precipitating a transfer of energy of the radiation to certain electrons in the matter traversed; that is, as producing the necessary condition for certain electrons to act as nuclei for condensation of energy from the radiation, a condensation which might under other conditions have occurred in the earlier layers. This condition is provided when the absorption-coefficient of the heterogeneous radiations reaches a certain critical value within the substance traversed. We have already compared this to a condensation (or evaporation) of the energy of the radiation, the energy becoming concentrated in certain electrons *

(6) Again, the discontinuity of figs. 2 and 3 occurs much less frequently when thin absorbing sheets are used than is the case when thick sheets are used. This, indeed, is shown by the results obtained for the "unintercepted" beams, for even these must pass through thin aluminium windows to the measuring electroscopes. In some experiments, these thin electroscope windows did show the J_2 discontinuity. That the discontinuity was really due to this thin aluminium window is evidenced by the fact that it was never obtained when the aluminium window was replaced by thin celluloid.

Thus in all these experiments—Case *a*—the apparent difference between the secondary (scattered) X-radiation and the primary X-radiation producing it is a consequence of the transmission of the radiation through the intercepting substance used to test the absorbability of these radiations. All the difference between the two appears abruptly at penetrating powers characteristic of these absorbing substances. Apart from these differences definitely associated with the testing material, the scattered and the primary radiations are exactly alike to a high degree of accuracy. If there be a difference it is less than one-tenth of the difference demanded by Compton's hypothesis, or alternatively there is less than one-tenth of Compton's hypothetical radiation.

Case *b*.

In many experiments the apparent difference between the secondary and primary radiations appears even for soft—low-frequency—radiation, and persists throughout a very great

* Barkla and Gladys Mackenzie, 'Nature,' June 20, 1925.

range of frequencies. This is the result which makes the nearest approximation to anything of the nature of a change such as is given by Compton's hypothesis. Let us examine it: the facts are these:—

The ratio of ionizations produced by the intercepted secondary and primary radiations (S'/P') is definitely less, and unless the intercepting sheets are very thin, this ratio S'/P' is *markedly* less than S/P. The difference between S/P and S'/P' depends, as one would expect, upon the thickness of the intercepting sheets. It indicates a true difference between the absorbabilities of the scattered and the primary radiations as usually measured. Suppose the radiation to be perfectly homogeneous, then the ratio of ionizations of unintercepted beams (S/P) is a measure of the relative intensities of secondary and primary radiations, *i. e.*

$$\frac{S}{P}=k\frac{I_s}{I_p}\frac{i_2}{i_1},$$

where I_s and I_p are the intensities of secondary and primary radiations, i_2 and i_1 the ionizing coefficients of these radiations, and k is a constant depending on the precise arrangement of apparatus; whereas the ratio of the intercepted beams

$$S'/P'=\frac{k\,I_s\,i_2\,e^{-\mu_2 x}}{I_p\,i_1\,e^{-\mu_1 x}},$$

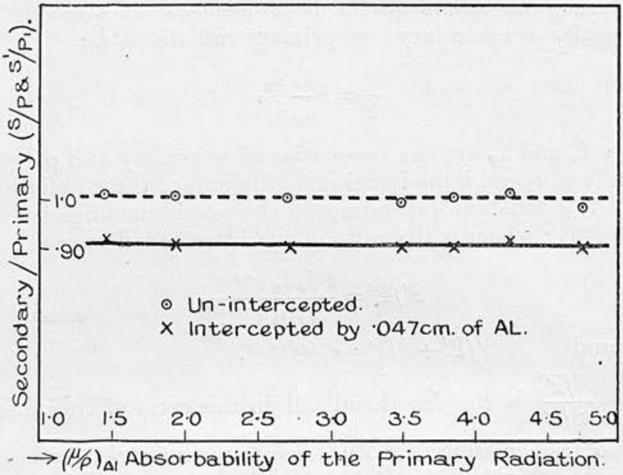
and $$S'/P'\div S/P=e^{-(\mu_2-\mu_1)x}.$$

$1-\dfrac{S'/P'}{S/P}$ is the fractional fall in the ratio of ionizations due to transmission of both secondary and primary beams through a thickness x of absorbing substance. This would equal $1-e^{-(\mu_2-\mu_1)x}$, and for small thicknesses should be proportional to the thickness x. This is found to be the case; $\dfrac{S/P-S'/P'}{S/P}$ varies just as we would expect if there were a true transformation of the radiation by scattering.

Such an experimental result as is described as Case *b*, if considered alone, would, of course, lead an observer to the conclusion that there was a change in the absorbability on scattering. But what do we find? The ratio of S'/P' to S/P is precisely the same in Case *b* as when we actually observe the discontinuity in Case *a*: that is, the change from S/P to S'/P' which in Case *b* appears to be produced in the scattering substance, is identical with what in Case *a* we observed to take place in the absorbing substance.

Thus in Case *b*, beginning with low-frequency radiation and gradually increasing the frequency, instead of observing the similarity of secondary and primary radiations at the low-frequency end and the various steps introducing a well-marked difference, we observe even with the softest radiation the difference which, in Case *a*, appears only after the first step, and this difference persists throughout the whole range of frequencies. This is illustrated in fig. 7, in which the ratio for intercepted beams, shown by the crosses, shows no discontinuity at either the J_1 or the J_2 point through which it passes.

Fig. 7.



It seems highly probable, therefore, that if we could sufficiently extend the range of wave-lengths experimented upon, a step like the J_1 step would be observed in the region of very low frequencies.

Be that as it may, the process by which the difference between secondary and primary beams is produced must be identical in the two cases. In cases which we can examine (Case *a*) the change of character is definitely not in the process of scattering. We must therefore conclude that, when the change takes place outside our range of direct experimental investigation, the process is identical in nature, and is therefore still not produced by scattering, or even by any process, call it what we may, by which the scattered radiation originates.

A second point is, that throughout a great range of wave-lengths, indeed throughout the full range of our experiments, the ratio $S'/P' \div S/P$, i. e. $e^{-(\mu_2-\mu_1)x}$, is so accurately constant. In numerous and extensive series of observations this has been most strikingly shown—that whatever the wave-length, the effect on this ratio of intercepting both primary and secondary radiations by a definite thickness of aluminium is independent of the wave-length. In other words, the ionizing power of the secondary radiation after transmission through a definite thickness of aluminium is a definite fraction less than that of the primary radiation similarly treated, whatever the wave-length of the radiation. This does not look like a wave-length change at all, for the result itself is a very simple one, whereas the change of wave-length on scattering required to produce it is not nearly so simple.

Thus let λ_1 and λ_2 be the wave-lengths of primary and secondary radiations respectively, and let $\lambda_2 = \lambda_1 + \delta$.

The coefficients of absorption of these radiations in aluminium may be written, at any rate to a first approximation, as

$$\left(\frac{\mu}{\rho}\right)_1 = k\lambda_1^3 + \frac{\sigma}{\rho} \quad \text{and} \quad \left(\frac{\mu}{\rho}\right)_2 = k(\lambda+\delta)^3 + \frac{\sigma}{\rho},$$

where k is a constant and $\frac{\sigma}{\rho}$ is the scattering coefficient in aluminium. Then

$$\left(\frac{\mu}{\rho}\right)_2 - \left(\frac{\mu}{\rho}\right)_1 = 3k\lambda^2\delta.$$

Experiment shows this to be constant; that is, $\delta \propto \frac{1}{\lambda^2}$.

Thus, to give such a simple experimental result, the change of wave-length on scattering would require to be approximately inversely as the square of the wave-length of the primary radiation. Closer approximation to accuracy would make this only more complicated.

This, again, is entirely at variance with Compton's hypothesis, which leads to the conclusion that δ is constant, *i. e.* that the change of wave-length on scattering is independent of the wave-length. On Compton's hypothesis $\left(\frac{\mu}{\rho}\right)_2 - \left(\frac{\mu}{\rho}\right)_1$ should then be proportional to λ^2, and our horizontal lines for S'/P' should be lines sloping down to the right.

Our experimental result, however, is simple, and is simply and accurately described :—The difference between secondary and primary radiations throughout a long range of wave-lengths is represented by a constant difference of absorption-coefficients. This simplicity of statement implies a simplicity of action. The improbability of a somewhat complicated law expressing the fundamental change of wave-length yielding a result of the simplest possible kind when expressed in terms of absorption-coefficient needs no emphazising. The constant change of absorbability seems to be the fundamental change.

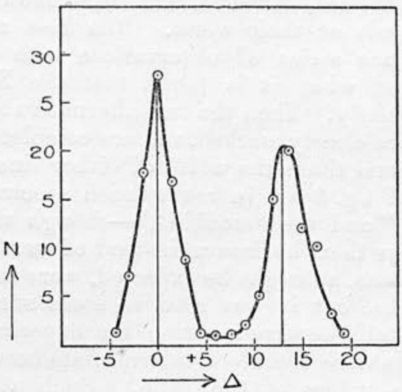
Again, if the change in the absorbability of the secondary radiation involved a real transformation of this radiation, say a wave-length change, this would necessarily involve also (1) a change in the energy of the radiation, (2) a change in the ionization-coefficient of such a radiation in the gas of the detecting electroscope (for ionization-coefficient normally varies as the cube of the wave-length approximately), as well as (3) a change in the absorption of such radiation in the intercepting sheets.

But in Case *a*, in which the change in certain limited regions near the J discontinuity is seen to take place in the absorbing substance, these three would all be effective in producing a difference between S'/P' and S/P, for when S/P is determined the change has not taken place; whereas in Case *b*, in which any change that there is takes place before the radiation falls on the intercepting sheets, (1) and (2) would have already affected S/P, so that the difference between S/P and S'/P' would be due to (3) alone. The fact that $\dfrac{S'/P'-S/P}{S/P}$ is identical in the two cases shows that (1) and (2) are both zero, or just possibly that they neutralize. The latter is most improbable though not impossible. There is a change in absorption-coefficient, but all the evidence is against a change in wave-length.

This is also shown, of course, in the filtering experiment (see figs. 5 and 6) in which the value of S'/P' is plotted against various values of x. When the discontinuity occurs with thin absorbing sheets the J step is certainly small, showing that the combined effect of a possible change of energy and change of ionization-coefficient is exceedingly small. But, though the evidence is strongly against a change of wave-length produced in the J_1 transformation, it cannot be regarded yet as completely conclusive. There still appear to be possibilities in connexion with the J_2 and J_3 transformations to which some of the above considerations do not seem to apply. These need further investigation.

The alternative nature of the two cases (*a* and *b*) is well illustrated by collecting all the observations, good and indifferent, obtained at various times with various experimental arrangements and showing their distribution. Fig. 8 shows by its ordinates the number of measurements plotted

Fig. 8.



Ordinate: Number of observations within the range of $\pm 0{\cdot}75$ per cent. of abscissa.

Abscissa: Percentage change of absorption-coefficient.

Displacement of $\left(\frac{\mu}{\rho}\right) = 13$ per cent. when $\left(\frac{\mu}{\rho}\right) = 5{\cdot}2$ or $5{\cdot}3$ average, *i. e.* Mo K_α.

against the observed difference between the absorption-coefficients of secondary and primary radiations when the primary radiation had an absorption-coefficient $\left(\frac{\mu}{\rho}\right)_{Al}$ in the neighbourhood of $5{\cdot}3$, which is the absorbability of Mo "K"-radiation upon which so many spectroscopic measurements have been made. The distribution curve shows two well-marked peaks, one corresponding to an absolutely unchanged radiation, and the other to a definite change of "absorption-coefficient" of 13 per cent.

This is suggestive of Compton's intensity curve showing the peaks obtained in one experiment and appearing to have been obtained simultaneously. In our experiments, however, these are not produced at the same time, but are alternative effects; and, in addition, our modified peak is due to a transformation taking place independently of scattering.

It happens, too, that in this region, where most of Compton's measurements have been made, the magnitude of the separation of our two peaks agrees very well with Compton's theoretical value for the wave-length change. Thus a 13-per-cent. change of absorption-coefficient would correspond to a change of wave-length of a little more than 4 per cent., which is Compton's change for Mo "K"-radiation. It should be noticed, however, that fig. 8 shows the results of our methods at their worst. The best are naturally obtained in one series of observations with one form of apparatus, and when it is found that the X-ray tube is working regularly. Then the two alternative spectral lines are much more clearly marked, and are completely separated by a gap several times the width of either line. The horizontal lines of fig. 3 are in reality such spectral lines—the "unmodified" and the "modified,"—though the method of drawing shows them horizontal instead of vertical. One or two observations, as might be expected, were found between the two peaks, but it was seen in some such cases that a change actually occurred during the experiment, and the final readings were therefore intermediate between the true instantaneous values of the ratio. Such values are, of course, included in fig. 8. It is practically certain that all such intermediate values, as they were so few, were the result of a change of the critical condition during the experiment, the unmodified radiation being effective during one portion of the time, and the modified during the remainder.

Summary.

The simplest and most direct experiments on the scattering of X-rays from paper show that when the scattered radiation is tested there is either (*a*) a very exact equality of penetrating powers of secondary and primary, or (*b*) a well-marked difference between the two. The difference when it appears is the result of the J transformation which occurs in matter during transmission of the radiation through that matter. In many cases, this is definitely subsequent to the emission of secondary radiation from the radiating substance ; and in the other cases, although the radiation when first tested appears to have been transformed, the transformation is exactly like that actually seen to occur outside the scattering sub-tance. The transformation then observed is thus not the result of scattering or of any process (call it what we may) by which the radiation originates.

The law giving the difference between the secondary and primary radiations is, as far as it is expressible in familiar terms, that between two J discontinuities the difference between the absorption-coefficients of primary and secondary radiations is a constant, viz.:

$$\left(\frac{\mu}{\rho_2}\right)=\left(\frac{\mu}{\rho_1}\right)+\text{constant}.$$

Thus, though we have made hundreds of comparisons between the secondary and primary X-radiations, we find only the difference due to what we have called the J phenomenon occurring in the scattered radiation. A change of wave-length which, according to Compton, is produced in the process of emission of the secondary radiation, quite clearly and definitely did not occur in such experiments.

It seems highly probable, however, that the displaced spectral line as observed by Compton and others is a result of the J phenomenon, for in place of Compton's results we find something corresponding to them expressible in terms of this much more general J phenomenon.

(1) Thus, instead of Compton's change of wave-length on scattering, we find that a scattered radiation which is indistinguishable from the primary radiation, under some conditions has its absorbability suddenly and definitely changed by transmission through matter. This is the J transformation observed elsewhere.

(2) Instead of the change of wave-length being general, we find the J transformation is conditional on factors other than the nature of substance traversed and wave-length of radiation.

(3) Instead of an unmodified and a modified scattered radiation appearing simultaneously, we find over a short period *either* one *or* the other.

(4) Instead of the primary and scattered radiations being distinguished by a constant difference of wave-length, we find that over the range between two J discontinuities there is a constant difference of absorbability, *i.e.* instead of $\lambda_2=\lambda_1+\text{constant}$, we find

$$\left(\frac{\mu}{\rho}\right)_2=\left(\frac{\mu}{\rho}\right)_1+\text{constant}.$$

(5) To these we may add a preliminary announcement of

the results of experiments conducted with Miss Gladys Mackenzie on the scattering at various angles :—

> Instead of a difference in the wave-lengths of scattered radiations proceeding in directions making angles of 60° and 120° with the primary beam, we find *either* (*a*) the two scattered beams have precisely the same absorbability between J discontinuities, but the beam at 120° shows the discontinuites, the other does not ; *or* (*b*) the radiation at 120° is continuously more absorbable than the other.
>
> This dependence on some unknown critical condition is characteristic of the J phenomenon.

What then is the J phenomenon? It is too new and too comprehensive to describe in a few words. But it appears that all the phenomena due to X-rays—the activity of an X-radiation—depends in part (possibly entirely) on a coherence of constituent radiations, and that a slight change of condition alters the activity of the X-radiation from one definite level to another. There are various levels of activity dependent not on individual harmonic constituents of a complex radiation, but on the radiation as a whole. The J discontinuities are the steps from one level to another, and the change of activity is the J transformation.

As the activity resulting in corpuscular emission, ionization, photographic action, etc., does not vary continuously with wave-length, anomalies may as a consequence appear in spectrometer work. Appreciable refraction may also occur in a crystal when the absorption suddenly changes at a J discontinuity.

Be that as it may (and the suggestions are not too promising), the evidence we have obtained seems strongly against a change of wave-length, at any rate as ordinarily understood, even when the J_1 transformation occurs. But the phenomenon is so new and opens up such vast possibilities that we must still regard it as an open question, with the balance of evidence strongly against. This, however, is a question concerned with the J phenomenon and not scattering or anything resembling it, though it is probable that the process of scattering in some cases (Case *b*) produces the necessary condition for a change of activity of the radiation from one level to another, and so indirectly involves the J transformation. Such a transformation may, however, be produced by other means and in radiations other than scattered radiations.

[To be continued.]

III

THE "MODIFIED SCATTERED" X-RADIATION

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THE "MODIFIED SCATTERED" X-RADIATION

MAY we now supplement what we have already told regarding the scattering of X-rays by stating that we now know quite definitely that even after the *J*-transformation has taken place in a scattered X-radiation and this has become a "modified scattered" radiation when its absorbability is measured in certain substances, it has, even after passing through those substances, precisely the same absorbability as the primary when measured in certain other substances.

This is in perfect agreement with the generalisation we have already made that there are various definite levels of activity of an X-radiation in any substance, the level depending upon the whole of a more or less complex beam, and that a change of the activity in one substance from level to level may take place without the least indication of any corresponding change in a second substance. What we have now found is, that the penetrating powers of secondary and primary radiations are equal in some substances *subsequent* to transmission through plates of material which exhibit or produce the difference.

What then of Compton's hypothesis, and more important still, the second line obtained in the spectrum of the scattered radiation? Can the wave-length of a radiation change without producing a corresponding change in absorption in *all* substances?

In answer, we must point out that we have already demonstrated that a change in the activity (photoelectric action, ionisation, absorption) of a radiation can take place without a change in the wave-length—that wave-length and material substance are not the only factors in X-ray phenomena. In order to reconcile our experimental results with Compton's hypothetical change of wave-length, we should be compelled to go further and state that a change of wave-length may take place without a corresponding change in activity—that is, we should be obliged to dissociate the properties of an X-radiation from wave-length altogether, or at any rate we should have to assume that within certain limits, absorption, electronic emission, etc., are independent of wave-length.

Consequently we are very sceptical as to whether a change in the diffraction angle in spectroscopic measurements really does correspond to a change of wave-length. A measurement of absorption is purely experimental, but a measurement of wave-length is dependent on the adequacy of the classical theory of diffraction, and assumes the absence of any unforeseen phenomenon.

It is an experimental fact that the critical condition which governs the change of activity which we have called the *J*-phenomenon is not wave-length, but something analogous to " temperature " of the whole beam of X-rays. Our critical condition for the excitation of the *J*-electronic emission, *J*-ionisation and *J*-absorption is not that the frequency of the primary beam should be higher than a certain critical value, but that this " temperature " shall be higher than a certain value. Thus in place of Stokes' Law which we found to hold for K and L radiations, we find that in the case of the *J*-phenomenon at least, we may write T_1 must be greater than T_2 where T_1 is the average penetrating power (" temperature ") of the beam and T_2 is a penetrating power characteristic of the substance traversed. We use the term " temperature " only tentatively because it is a familiar physical quality which represents most closely, or is analogous to, the state of a complex radiation as measured by penetrating power by ionisation-absorption methods. It seems just possible that Stokes' Law may need to be re-stated in some such way in order to make it more general, and to express what is most fundamental. This, however, is speculative: the experimental facts we have recorded are in a different category altogether; they are beyond dispute.

To summarise, we must accept one of the following possible alternatives:

(1) The second spectral line in Compton's experiments does not represent another wave-length in the secondary radiation incident on the crystal of the spectrometer, or

(2) Wave-length may change without a corresponding change in the activity of an X-radiation. This seems possible only on the assumption of the dual nature of radiation in some such way as is suggested by Sir J. J. Thomson, or

(3) The conditions essential to the production of the second spectral line in the spectrum of scattered X-radiation have not been realised in the hundreds of experiments we have made on the phenomenon. This is highly improbable both from the variety of our experiments and from the fact that we do under some conditions obtain what has the *superficial appearance* of a change of wave-length.

The alternative probabilities are thus reduced to (1) and (2).

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Nature, April 25, 1925.

Spectroscopic Evidence of *J*-Transformation of X-rays.

The relation between the atomic number of a radiator and the wave-lengths of its X-ray emission spectrum of *K*-series is generally assumed to be the regular one described by Sommerfeld's extension of Bohr's idea to X-ray spectra. Well-marked irregularities, however, have not received attention in the literature of the subject; it is the object of this note to direct attention to them.

Fig. 1 shows the variation of the wave-lengths $K\alpha_1$, and K_A (absorption limit) with atomic number (Z) of radiator from Z = 40 to Z = 60; the plotted values are from Siegbahn, and Blake and Duane respectively. Fig. 2 is an enlargement of Fig. 1, to show more clearly the irregularities which we shall proceed to describe. If we follow λ for $K\alpha_1$, as Z is increased

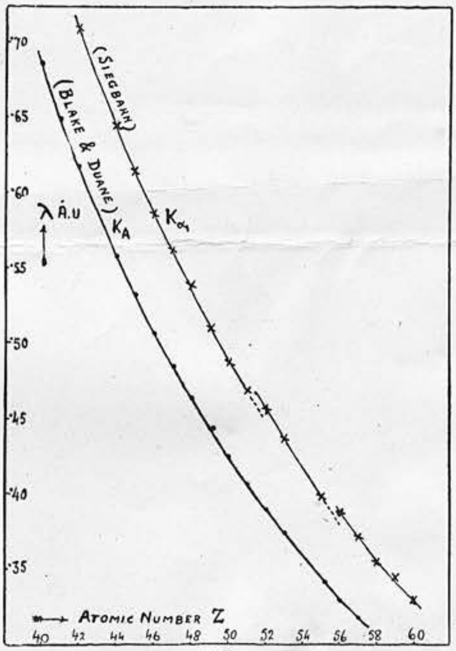

Fig. 1.

from 40, we notice that at Z = 52 and at Z = 56 there takes place a sudden increase in λ relative to the value which would have occurred were the simple relation for smaller atomic numbers obeyed. The magnitude of this excess is about 0·01 Å.U. in each case. Exactly the same irregularities occur in $K\alpha_2$ and $K\beta$, but not in K_A. Lack of data prevents any definite conclusion with regard to $K\gamma$. The degree of precision claimed for these spectroscopic observations is too high to admit of any other conclusion than that these irregularities are real deviations from the simple law.

It is certainly no fortuitous coincidence that the wave-lengths at which these sudden increases take place, correspond very well with two of the critical absorbabilities for *J*-transformation, which in the case of aluminium are (μ/ρ)Al = 1·9 and 0·7 (see Bakerian Lecture by Barkla, Phil. Trans. 1917, and Barkla and White, *Phil. Mag.* 34, Oct. 1917), and which are only very slightly displaced by change of the atomic number of the transmitting element except when this is small. The atomic structure of the radiator cannot be supposed responsible for the irregularities referred to, for, at the atomic numbers indicated, there is no readjustment of electronic distribution according to the Bohr scheme. As there is no reason, either

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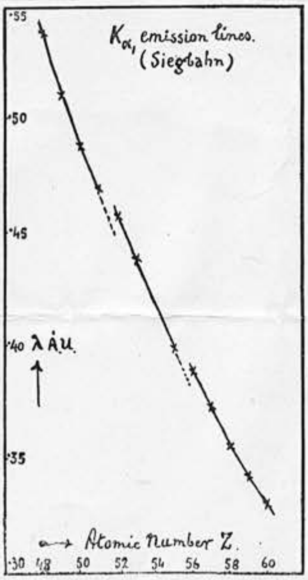

FIG. 2.

theoretical or practical, for the occurrence of these irregularities, apart from the *J*-transformation, and as they appear precisely in the same place as in the experiments showing *J*-discontinuities, one can only conclude that these irregularities are due to the *J*-transformation of X-radiation taking place in the calcite crystal used for the analysis of the radiation or possibly in the anticathode or walls of the X-ray tube. We have, however, no information of the crystal used by Blake and Duane for the measurement of *K*A.

This seems to be the first spectroscopic evidence of the *J*-transformation, which by absorption methods has been found in primary rays (Barkla, Silvanus Thomson Lecture, NATURE Nov. 22, 1924) and in scattered rays (Barkla and Khastgir, *Phil. Mag.* 49, Jan. 1925). This also strongly supports the view expressed by Barkla (NATURE, Nov. 17, 1923, and Nov. 22, 1924) that the apparent increase of wave-length as observed by Compton and others in the scattered radiation is due to the same *J*-transformation during transmission in the crystal or in the radiator, and is not part of the phenomenon of scattering at all. That the magnitude of the change appearing in the curves shown here is of the order of the Compton shift, gives further support to this contention. It must be understood, however, that the attainment of a critical wave-length is not the only factor which determines whether or not the transformation takes place.

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